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ROUND TRIP TO ORBIT

Human Spaceflight Alternatives

Special Report

CONGRESS OF THE UNITED STATES

OFFICE OF TECHNOLOGY ASSESSMENT

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Human Spaceflight Alternatives

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Foreword

In the 20 years since the first Apollo moon landing, the Nation has moved well beyond the Saturn 5 expendable launch vehicle that put men on the moon. First launched in 1981, the Space Shuttle, the world's first partially reusable launch system, has made possible an array of space achievements, including the recovery and repair of ailing satellites, and shirtsleeve research in Spacelab. However, the tragic loss of the orbiter *Challenger* and its crew three and a half years ago reminded us that space travel also carries with it a high element of risk—both to spacecraft and to people.

Continued human exploration and exploitation of space will depend on a fleet of versatile and reliable launch vehicles. As this special report points out, the United States can look forward to continued improvements in safety, reliability, and performance of the Shuttle system. Yet, early in the next century, the Nation will need a replacement for the Shuttle. To prepare for that eventuality, NASA and the Air Force have begun to explore the potential for advanced launch systems, such as the Advanced Manned Launch System and the National Aerospace Plane, which could revolutionize human access to space. Decisions taken now will affect the future of spaceflight in the 21st century.

This special report examines a wide range of potential improvements to the Space Shuttle, explores the future of space transportation for humans, and presents policy options for congressional consideration. It is one of a series of products from a broad assessment of space transportation technologies undertaken by OTA, requested by the Senate Committee on Commerce, Science, and Transportation, and the House Committee on Science, Space, and Technology. In the past year, OTA has published a special report, *Launch Options for the Future: A Buyer's Guide*, a technical memorandum, *Reducing Launch Operations Costs: New Technologies and Practices*, and a background paper, *Big Dumb Boosters: A Low-Cost Space Transportation Option?*

In undertaking this effort, OTA sought the contributions of a wide spectrum of knowledgeable individuals and organizations. Some provided information, others reviewed drafts. OTA gratefully acknowledges their contributions of time and intellectual effort. OTA also appreciates the help and cooperation of NASA and the Air Force. As with all OTA reports, the content of this special report is the sole responsibility of the Office of Technology Assessment and does not necessarily represent the views of our advisors or reviewers.

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Related OTA Reports

Civilian Space

Advanced Space Transportation Technologies Assessment

- *Launch Options for the Future: A Buyer's Guide.* OTA-ISC-383, July 1988. GPO stock #052-003-01117-4; $5.00.
- *Reducing Launch Operations Costs: New Technologies and Practices.* OTA-TM-ISC-28, September 1988. GPO stock number #052-003-01118-2; $4.50.
- *Big Dumb Boosters: A Low-Cost Space Transportation Option?:* OTA Background Paper, February 1989.
- *Commercial Newsgathering From Space:* OTA-TM-ISC-40, May 1987. GPO stock #052-003-01066-6; $3.00.
- *Space Stations and the Law: Selected Legal Issues.* OTA-BP-ISC-41, September 1986. GPO stock #052-003-01047-0; $3.75.
- *International Cooperation and Competition in Civilian Space Activities.* OTA-ISC-239, July 1985. NTIS order #PB 87-136 842/AS.
- *U.S.-Soviet Cooperation in Space:* OTA-TM-STI-27, July 1985. GPO stock #052-003-01004-6; $4.50.
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- *Remote Sensing and the Private Sector: Issues for Discussion.* OTA-TM-ISC-20, March 1984. NTIS order #PB 84-180 777.
- *Salyut: Soviet Steps Toward Permanent Human Presence in Space:* OTA-TM-STI-14, December 1983. GPO stock #052-003-00937-4; $4.50.
- *UNISPACE '82: A Context for International Cooperation and Competition:* OTA-TM-ISC-26, March 1983. NTIS order #PB 83-201 848.
- *Space Science Research in the United States:* OTA-TM-STI-19, September 1982. NTIS order #PB 83-166 512.
- *Civilian Space Policy and Applications:* OTA-STI-177, June 1982. NTIS order #PB 82-234 444.
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- *Solar Power Satellite Systems and Issues:* OTA-E-144, August 1981. NTIS order #PB 82-108 846.

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- *SDI: Technology, Survivability, and Software:* OTA-ISC-353, May 1988. GPO stock #052-003-01084-4; $12.00.
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- *Directed Energy Missile Defense in Space:* OTA-BP-ISC-26, April 1984. GPO stock #052-003-00948-0; $4.50.

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Congressional Alternatives for Crew-Carrying Launch Systems

If Congress wishes to continue to improve the safety, reliability, performance, and/or economy of crew-carrying launch systems, it has a number of alternatives from which to choose. Several are listed below; they are not mutually exclusive, nor is the list exhaustive. Congress could decide to proceed with one or more from each list of options.

Because of the long lead times for the development of space transportation systems, some decisions will have to be made in the next year or two. Others can wait until the middle of the next decade or later.

Near-Term Decisions

If Congress wishes to:	*Then it could:*
Improve Shuttle system safety and reliability: (*See ch. 3.*)	• *Fund development of Liquid-fueled Rocket Boosters (LRBs).* • *Fund continued development and improvement of Advanced Solid Rocket Motors (ASRMs) and alternate turbopumps for the Space Shuttle Main Engines* • *Fund continued gradual improvement of Redesigned Solid Rocket Motors (RSRMs).* • *Fund installation of built-in test equipment in the Shuttle and more automated test equipment in launch facilities.* *High confidence* in the safety or reliability of LRBs, ASRMs or other new systems would require many flight tests.
Improve Shuttle system performance (payload carried per flight): (*See ch. 3.*)	• *Fund development of LRBs.* • *Fund continued development of ASRMs.* • *Fund improvement of RSRM thrust.* • *Fund development of lighter External Tanks.* • *Fund procurement of a new orbiter made of new, lightweight materials.* • *Fund procurement of a new orbiter capable of flying unpiloted.* LRBs offer the greatest performance increase. In principle they could lead to improved mission safety.
Maintain a sustainable Shuttle launch rate of 9 to 11 launches per year: (*See ch. 3.*)	• *Fund the purchase of at least one additional orbiter to be delivered as soon as possible (1996), and direct NASA to minimize the number of Shuttle flights flown per year. NASA could reduce Shuttle flights by:* *a. postponing or cancelling some planned Shuttle launches; or* *b. relying more on expendable launch vehicles, such as Titan IVs.*

A four-orbiter fleet is required to sustain a Shuttle launch rate of 9-11 launches per year. Shuttle reliability is uncertain but may lie between 97% and 99%. If it is 98%, there is a 50% probability of losing one orbiter about every three years assuming a launch rate of 11 per year. Higher launch rates would require additional launch facilities.

Purchasing an additional orbiter would provide a hedge against attrition. Minimizing the number of flights per year would reduce the probability of attrition before *Endeavour* enters service.

Reduce risks to fleet capabilities during Space Station assembly:

(*See ch. 3.*)

- *Direct NASA to buy and use Titan IV launch vehicles, or develop and use Shuttle-C launch vehicles, to carry some Space Station elements to orbit.*
- *Fund immediate procurement of one or more additional orbiters.*

The first option would reduce the number of Shuttle flights required for assembly (from 21 to 10, if Shuttle-C is used) and the risk to the Shuttle and Shuttle crews. The second option would hedge against the effects of attrition.

Reduce risks to successful Space Station assembly:

(*See ch. 3.*)

- *Direct NASA to develop and use Shuttle-C to carry some Space Station elements to orbit. (This would reduce the total number of flights required and might reduce the risk of losing an element.)*

Develop the technology base for building new crew-carrying launch systems:

(*See chs. 4 & 5.*)

- *Continue to fund technology development and test efforts such as:*
  - *a. the National Aero-Space Plane program; or*
  - *b. the Advanced Launch System program.*

ALS or NASP technology could be used in the Personnel Launch System or the Advanced Manned Launch System proposed by

Provide for emergency crew return from the Space Station:

(*See ch. 6.*)

- *Fund a program to develop:*
  - *a. a capsule for Space Station escape; or*
  - *b. a glider for Space Station escape.*

However, the improvement to Space Station crew safety that a crew emergency return vehicle might provide is highly uncertain.

Far-Term Decisions

If Congress wishes to:	*Then it could:*
Build safer, more reliable crew-carrying launch systems: (*See chs. 4 & 5*)	• *Fund development of safer, more reliable launch systems to augment or succeed the Shuttle. These might include:* *a. a Personnel launch system (PLS), or* *b. an Advanced Manned Launch System (AMLS), or* *c. vehicles derived from the National Aero-Space Plane program.* These systems are being designed to survive some types of engine failure and could have crew escape systems. However, designs have not been chosen, nor have detailed safety assessments been performed.
Improve launch system reliability: (*See chs. 3, 4, 5*)	• *Fund development of launch vehicles or systems (e.g. Space Transportation Main Engines) that could be manufactured, integrated, and launched by highly automated methods with improved process control. Fault-tolerant system design may be useful if critical components are not sufficiently reliable.*
Lower launch cost: (*See chs. 4&5*)	• *Fund development of vehicles designed for quick turnaround, such as those being considered for an Advanced Manned Launch System or as possible successors to the proposed National Aero-Space Plane test vehicle (X-30).* Vehicles derived from the NASP X-30 may have greater potential to reduce launch costs compared with two-stage AMLS configurations. However, they would be more risky to develop and would likely be available later.

Selected Options for Improving the Space Shuttle System

The following options were selected from a wide range of possible improvements to the Space Shuttle System. The effectiveness of each option represents OTA's considered judgement. However, each may be more or less effective depending upon other improvements chosen and the pace at which they are implemented.

Options	Objectives: Improve Shuttle safety and/or reliability	Increase Shuttle system performance (payload per flight)	Maintain capability to sustain Shuttle launch rate of 9-11 per year	Extend the life of the current orbiter fleet	Increase the probability of assembling Space Station on schedule	Provide for emergency crew return from space	Prepare for the development of future launch systems
Major investment							
1. Continue to develop the Advanced Solid Rocket Motors (ASRMs)	★★	★★			★★		
2. Fund development of Liquid Rocket Boosters (LRBs)	★★★	★★★		★	★		★★★
3. Develop Shuttle-C				★★	★★★		★
4. Fund purchase of one or more additional orbiters			★★★	★	★★★		
5. Fund development of capsule or glider for Space Station escape						★★★	★
6. Institute integrated long-term program to improve reliability, safety, and performance of Space Shuttle system	★★★	★★★		★★	★★★		★
Supporting improvements							
1. Continue to improve the Redesigned Solid Rocket Motors (RSRMs)	★	★	★		★		
2. Incorporate built-in test equipment in existing launch vehicles and develop additional automated test equipment for launch facilities	★		★★	★			★★★
3. Develop lighter weight External Tank (ET)		★★					★
4. Develop lightweight structures for Shuttle orbiter		★★					★
5. Modify orbiter for automatic flight capability	★	★				★	★
6. Fund technology development and test efforts	★★★	★		★★	★		★★★
7. Shift all payloads not requiring crews from Shuttle to expendable launch vehicles to reduce Shuttle flight rate			★★	★★	★★		

KEY: ★★★ = Very effective
★★ = Moderately effective
★ = Somewhat effective

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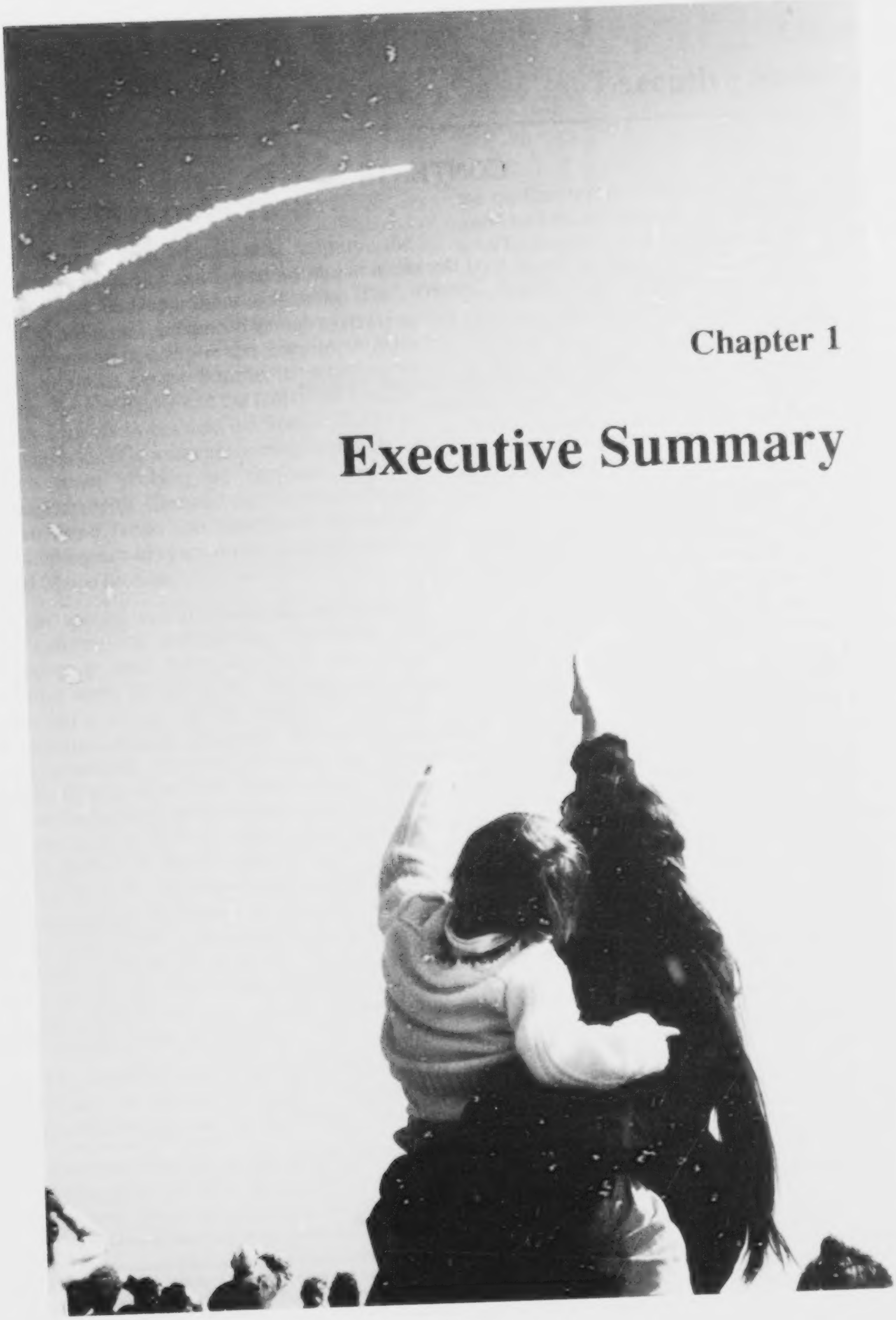

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Executive Summary

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Chapter 1

Executive Summary

INTRODUCTION

In the early part of the next century, the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD) intend to build new, advanced launch systems to carry crews to space. In the interim, NASA hopes to make Space Shuttle launches more routine. Between now and the end of the century NASA expects to employ the Space Shuttle to conduct scientific and engineering research, to launch space probes and satellites, and—in partnership with Canada, the European Space Agency, and Japan—to establish a permanent human presence in space on the planned international Space Station.

This special report examines technologies and systems for transporting astronauts and scientists to and from low-Earth orbit, and explores some of the policy choices that Congress faces in this critical aspect of the U.S. Government's space program. The report analyzes a variety of ways to make the Space Shuttle system safer and more reliable. It also explores several proposed systems to replace the Shuttle early in the next century, and examines proposals for a Space Station crew escape system. Finally, the report discusses the most advanced proposed launch system, the National Aero-Space Plane, and compares it with other potential future launch systems. The report does not examine cargo-only launch vehicles except insofar as their use may affect the need for crew-carrying launchers.

OTA prepared this special report as part of an assessment of advanced space transportation technologies requested by the Senate Committee on Commerce, Science, and Transportation and the House Committee on Science, Space, and Technology. For this assessment, OTA has previously published a special report, *Launch Options for the Future: A Buyer's Guide*;[1] a technical memorandum, *Reducing Launch Operations Costs: New Technologies and Practices*,[2] and a background paper, *Big Dumb Boosters: A Low-Cost, Transportation Option?*[3] A final report will summarize the findings of these interim documents.

PEOPLE IN SPACE

Since 1961, when President Kennedy called for a program to send men to the moon and back, NASA's "manned"[4] space efforts have determined much of the direction and spending of the government's civilian space program. Today, NASA's projects involving humans in space, primarily the existing Space Shuttle and the planned Space Station, consume between 65 and 70 percent of NASA's space budget, or between $6.8 billion and $7.3 billion in fiscal year 1989.[5]

From the early days of the U.S. space program, experts have argued over the appropriate mix of crew and automated civilian space activities. Although employing people in space to conduct most science research and exploration dramatically raises the costs compared to automated approaches, the perceived national and international benefits of having U.S. and foreign citizens live and work in space have nevertheless sustained the human component of the civilian space program.

Assessing the most appropriate mix of spending on automated and crew-dependent activities is beyond the scope of this report. However, **existing U.S. policy calls for expanding "human presence and activity beyond Earth orbit into the solar system."[6] Pursuing this policy in earnest would eventually require markedly increased funding of the government's civilian activities involving people in space, and therefore additional space transportation capability.** Major projects requiring crews in space could include the construction of a permanent base on the Moon, or the exploration of Mars. These, or other projects in the early part of the next century, would require the support of substantial in-orbit infrastructure, such as a space station, orbital maneuvering vehicles, and fuel storage depots. The pace and timing of such expansion will depend on the willingness of Congress, on behalf of U.S. taxpayers, to support such activities in competition with other uses of public monies.

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[1] U.S. Congress, Office of Technology Assessment, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988).

[2] U.S. Congress, Office of Technology Assessment, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

[3] U.S. Congress, Office of Technology Assessment (Washington, DC: Office of Technology Assessment, February 1989).

[4] The terms piloted or crew-carrying are used in this report in lieu of "manned."

[5] These figures exclude $404 million for aeronautics. The fiscal year 1990 civilian space budget request of $12.8 billion (which excludes $463 million for aeronautics) allocates about 71 percent to programs supporting crews in space. Most of President Bush's 20 percent requested budget increase for NASA for fiscal year 1990 derives from scheduled increases in the request for the Space Station.

In contrast to the civilian space program, the DoD has not identified a firm requirement for placing people in space.[7] However, if military needs were eventually to dictate a requirement for the procurement of a fleet of aerospace planes, as is contemplated by supporters of the National Aero-Space Plane program, this development could lead to a major commitment by the DoD to crews in space.

Expanded commitment to placing crews in space for the civilian and/or military space programs would eventually entail developing new launchers and other space vehicles capable of transporting people. It would also require increased yearly outlays for space transportation.

Spaceflight is inherently risky. As America's reaction to the *Challenger* disaster suggested, the loss of another Shuttle orbiter and its crew would likely result in another long standdown of the Space Shuttle, with attendent loss of momentum in the civilian space program. It would most certainly lead to a painful reexamination of the space program's purpose and direction. Yet, as the following section makes clear, the United States should expect the loss of another orbiter (though not necessarily with loss of life) at some time in the next decade. **If the United States wishes to send people into space on a routine basis, the Nation will have to come to grips with the risks of human spaceflight. In particular, it will have to accept the likelihood that loss of life will occur. If such risks are perceived to be too high, the Nation may decide to reduce its emphasis on placing humans in space.**

SPACE TRANSPORTATION OPTIONS FOR THE NEXT DECADE

NASA and the aerospace community have begun to consider how best to maintain or enhance crew-carrying capacity for the next decade, as well as for the beginning of the next century. Decisions concerning systems that would be developed for use in the next decade must be made in the immediate future because of the lead times required for these highly complex systems. Cost and schedule will constrain the decisions on these systems.

Purchasing Additional Space Shuttle Orbiters

To reduce the risk of costly delay in constructing or operating the Space Station, or meeting other NASA and DoD missions, NASA will have to add one or more orbiterss to its existing Shuttle fleet by the mid-1990s and restrict the use of Shuttle to essential payloads. Current plans call for reaching 14 Shuttle flights per year by 1993, one year after NASA expects to add orbiter OV-105 (*Endeavour*), now under construction, to the fleet to replace *Challenger*. If the existing three orbiters[8] are still operating at that time, the Shuttle fleet will then consist of four orbiters. However, continued dependence on only four orbiters could be risky (figure 1-1). Launching each orbiter three or four times every year creates a growing cumulative risk of accidents or "wear out;" supporting the Space Station in addition to other crew-related missions would be difficult if not impossible with fewer than four orbiters. In addition to adding resilience to Space Station operations, building one or more additional orbiters would also help preserve existing expertise and manufacturing ability.

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[6] The White House, "National Space Policy," Fact Sheet, Feb. 11, 1988, p. 1.

[7] Indeed, the Secretary of Defense recently decided to cut spending on the National Aero-Space Plane program dramatically.

[8] The fleet now consists of *Columbia, Discovery*, and *Atlantis*.

If major structural spares[9] were in the inventory, construction of an additional orbiter would take about 5 years and cost about $2.5 billion, including the cost of replacing the spares. In the absence of structural spares to draw on, construction would take about 6 years. Therefore, should Congress decide that it is important to have another orbiter as soon as possible (1996), it could either:

- fund NASA to build an additional orbiter starting in fiscal year 1990; or
- fund NASA to order structural spares in fiscal year 1990 and defer a final decision on whether to build the orbiter until the fiscal year 1991 budget is decided.

Some structural spares are needed for the existing fleet in any case, so a decision in 1990 to purchase structural spares would not commit Congress to fund construction of an additional orbiter, but could provide necessary backup to the four-orbiter fleet.

Improving the Space Shuttle

NASA is considering ways to extend the useful lifetime of the Shuttle fleet by replacing or enhancing Shuttle subsystems, such as avionics, structural components, and computers, and by improving launch operations procedures (box 1-A). Improvements, some of which have been made or are under way, might keep the Shuttle fleet flying until 2010 or beyond.[10] *Minor improvements* to the existing orbiter, external tank, solid rocket boosters, and facilities could be accomplished during the regularly scheduled structural inspection program (every 3 years). *Major improvements* to orbiters would take a substantial commitment of NASA's energies, and a major funding commitment from Congress. Improvements in the form of weight reduction modifications or performance increases could boost the Shuttle's carrying capacity or provide the opportunity to construct an enhanced crew escape capability.

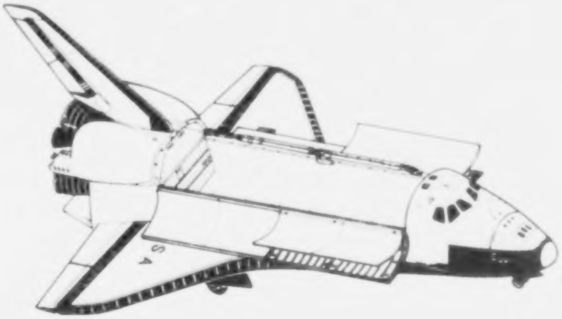

Photo credit: National Aeronautics and Space Administration

Drawing of Space Shuttle orbiter, showing payload bay doors open.

There is no way to know with certainty when it is wiser to improve existing technology (the evolutionary approach) or to leap to a new generation of technology (the revolutionary approach). Historically, the Nation has followed a revolutionary path of technology development when the perceived important future needs could not be met by improving the existing system, or when breakthroughs in technology made dramatic new systems possible. **Neither of these conditions exist today with respect to the Shuttle system. Evolutionary improve-**

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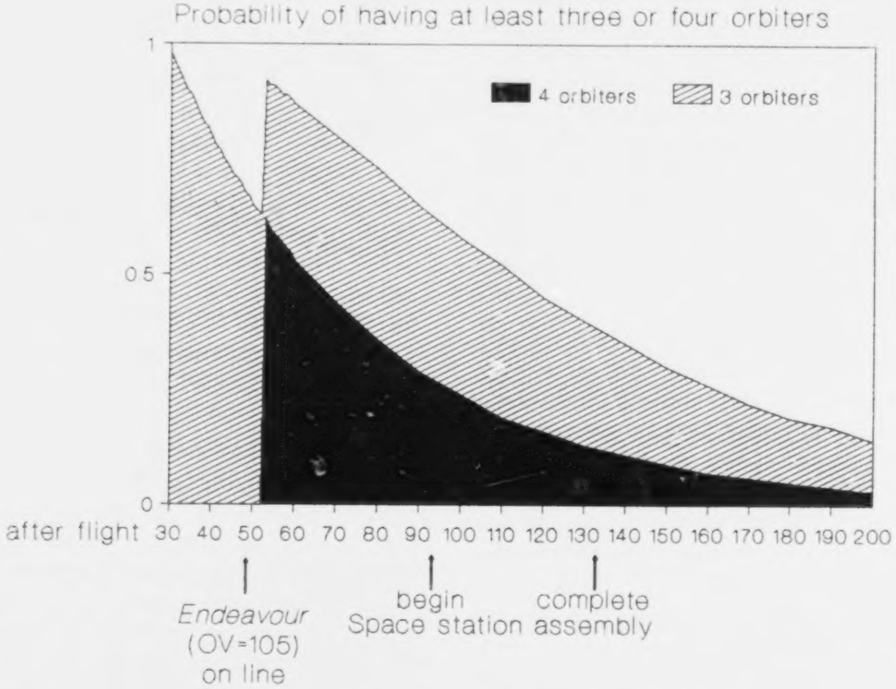
[9] Such as the aft fuselage module, crew compartment module, or wings.

[10] Estimates of the lifetime of the Shuttle fleet vary from about 2005 to 2020, depending on the flight rate, proposed upgrades, and number of orbiters purchased.

Figure 1-1—Shuttle Fleet Attrition if Orbiter Recovery Reliability is 98 percent.



Shuttle reliability is uncertain, but has been estimated to range between 97 and 99 percent.[1] If the Shuttle reliability is 98 percent, there would be a 50-50 chance of losing an orbiter within 34 flights. At a rate of 11 flights per year, there would be a 50 percent probability of losing an orbiter in a period of just over three years. The probability of maintaining at least three orbiters in the Shuttle fleet declines to less than 50 percent after flight 113.

Although loss of an orbiter would not necessarily result in loss of life, it would severely impede the progress of the civilian space program, as it would likely lead to a long standdown of the orbiter fleet while the cause of the failure was determined and repaired. Seen in terms of Space Station construction, if the probability of recovering an orbiter were 98 percent, the probability of retaining four operational orbiters would be only 28 percent when Space Station construction begins on flight 92 and only 12 percent when the Phase I Space Station is completed 42 flights later.

[1] L-Systems, Inc., *Shuttle/Shuttle-C Operations, Risks, and Cost Analyses*, LSYS-88-008 (El Segundo, CA: 1988).

SOURCE: Office of Technology Assessment, 1989.

ments would allow NASA to increase human spaceflight capabilities incrementally for lower cost and technical risk than would be the case for a whole new generation of vehicles. However, if the Nation were to decide to pursue major programs for people in space, such as a lunar base or a mission to Mars, revolutionary technological advances would be needed to increase capabilities and reduce operating costs.

Congress is faced with several options for enhancing the capabilities of the Shuttle system or improving its safety and reliability:

Enhance the Performance of the Redesigned Solid Rocket Motors (RSRMs)

Following the *Challenger* disaster, NASA redesigned the Shuttle's solid rocket boosters to increase their safety and reliability. At that time, it did not attempt to enhance booster performance. The payload capacity of the Shuttle could be increased by 6,000 to 8,000 pounds by substituting more energetic propellant, changing the motor's thrust profile, and redesigning

Box 1-A—Maintaining and Improving the Current Shuttle System

Buying Additional Orbiters

Three basic options are available:

- *Build a copy of OV-105*
  The *Challenger* replacement (OV-105), already being built, includes several important improvements:
  —addition of an escape hatch and pole;
  —improved heat shielding tiles, strengthened landing gear, wing structure, and engine pod;
  —more than 200 internal changes, including electrical rewiring and improvements in the braking and steering systems.
- *Implement additional improvements*
  —Safety/Reliability;
  —Cost Reduction; and
  —Performance.
  (Some of these upgrades may involve structural changes, and therefore could not be made in existing vehicles.)
- *Reduce airframe weight*—Orbiter airframe weight reduction of 8,000 to 10,000 pounds could be achieved through the use of
  —composite materials;
  —alloys;
  —intermetallics; and
  —high temperature metallics.

Incremental Changes

Some alterations to the Space Shuttle system have already been accomplished, or are already under way:

- *Redesigned Solid Rocket Motors (RSRM's)*
- *Space Shuttle Main Engine Improvements*—Specific efforts directed at longer life and higher reliability include improved:
  —welds;
  —manufacturing techniques;
  —nondestructive testing;
  —heat exchangers;
  —controllers;
  —engine health monitoring; and
  —turbopumps.
- *On-Board Computer Upgrades*—Specific efforts include:
  —identical computer modules "mass-produced" for economy
  —connection by optical fibers
  —a high degree of fault-tolerance

Other improvements NASA has considered or is now working on:

- *Extended Duration Orbiter (EDO)*—NASA is building in the capacity to extend on-orbit stays from the current 7 days to 16-28 days.
- *Automatic Orbiter Kit*—An existing Shuttle orbiter could be given the capability to fly an entire mission automatically.
- *Operations Improvements*—Introducing a number of new technologies and management strategies to make Shuttle launch operations more efficient and cheaper, e.g., improved Shuttle tile inspection and repair, and expert systems for control.

Major Changes

Some candidates include:

- *Advanced Solid Rocket Motors (ASRMs)*—These would replace the existing RSRMs. Compared to the RSRMs, they offer:
  —up to 12,000 pounds additional lift capacity
  —better manufacturing reproducibility
  —reduced stress on the Space Shuttle Main Engines
  —potentially higher reliability
  —potential for enhancing competition
- *Improve Redesigned Solid Rocket Motors*—The existing RSRMs could be improved further by redesigning them to increase their thrust. The Shuttle's payload capacity could be increased by 6,000 to 8,000 pounds by substituting a more energetic solid propellant and by making other requisite changes to the motors.
- *Liquid Rocket Boosters (LRBs)*—They would replace the solid boosters on the Shuttle. Compared to RSRMs, LRBs offer:
  —safer abort modes
  —up to 20,000 pounds additional lift capacity
  —long history, potentially greater mission reliability
  —capability of changing mission profiles more easily
  —safer Shuttle processing flow
  —potential application as an independent launch system
  —better environmental compatibility
- *Materials Improvements*—The emphasis on improved materials has focused particularly on saving weight. For example, using aluminum-lithium (Al-Li) for the external tank instead of the present aluminum alloy could provide a 20 to 30 percent weight savings. Using composite materials in the orbiter wings and other parts could save an additional 10,000 pounds.
- *Crew Escape Module*—This would allow for safe escape over a larger portion of the liftoff regime than now possible. It would replace the escape pole system presently in place, but would be heavier and much more costly.

its nozzle. NASA estimates such changes would require at least two years of development, testing, and qualification. However, adding a more energetic propellant might make the RSRM less reliable than it now is.

Continue To Develop the Advanced Solid Rocket Motor (ASRM)

NASA expects the ASRM to enhance Shuttle reliability and performance, and plans to use it starting in 1995 to replace the current, redesigned solid rocket motor. A 1987 National Research Council Report recommended development of the ASRM on grounds that it would "enhance both the performance and reliability of the post-Challenger Shuttle."[11] According to NASA, the ASRM would improve flight safety margins, system reliability, and payload capability. However, a recent report by NASA's Aerospace Safety Advisory Panel questioned whether the ASRM would provide sufficient additional safety and reliability when compared to the current RSRM.[12]

Using ASRMs might provide up to 12,000 pounds extra lift capacity and possibly reduce the number of Shuttle flights required to assemble the Space Station from about 21 to about 16.[13] NASA estimates that ASRMs would cost $1 billion for development and testing, and $300 million for facilities construction, and could be developed and tested in about 5 years. The report of the Aerospace Safety Advisory Panel suggested that NASA explore using this money instead for added safety improvements to other elements of the Shuttle system and said that "NASA has not thoroughly evaluated other alternative choices to the ASRM such as liquid rocket boosters."[14]

Develop a Liquid Rocket Booster (LRB)

Compared to solid rocket motors, LRBs offer improved performance, simpler launch operations, fewer environmental hazards, and, potentially, improved mission safety. They could provide from 12,000 to 20,000 pounds of extra payload capacity for the Shuttle. The development of the necessary new liquid-fueled engines for LRBs could be assisted by the research and development already underway in the joint Air Force/NASA Advanced Launch System program. However, LRBs offer greater development risk than the ASRMs and would likely cost more to develop. They might also take from 2 to 3 years longer to develop and test than the ASRMs.[15] NASA estimates that development, demonstration, test and evaluation for the liquid booster alone would cost $3 billion. It estimates that orbiter and pad modifications, which would be required to use the LRBs, might cost as much as $500 million. However, if an LRB could be powered by an engine requiring less ambitious development than that envisioned by NASA, the cost of the LRBs might be brought close to that of the ASRMs and might be available about the same time.[16]

Develop the Shuttle-C

Alternatively, NASA could obtain extra space transportation capability by building an expendable, unpiloted heavy-lift booster using Shuttle technology.[17] This "Shuttle-C" (for cargo) would use the recoverable solid rocket boosters, the same expendable external tank, and two refurbished main engines (SSMEs) from the Shuttle system. A large expendable cargo cannister, capable of transporting some 85,000 to 100,000 pounds of payload to low-Earth orbit would substitute for the Shuttle orbiter.

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[11] National Research Council, *Report of the Committee on the Space Station* (Washington, DC: National Academy Press, September 1987), p. 23.

[12] NASA's Aerospace Safety Advisory Panel questioned the "wisdom of proceeding with the procurement of a new solid rocket motor. . ." at this time. See National Aeronautics and Space Administration, *Aerospace Safety Advisory Panel Annual Report*, March 1989, p. iii, and p.3.

[13] Some propulsion experts, including some within NASA, have expressed concerns to OTA that the ASRM may not meet its performance goal. They base these concerns on experience with other space systems that have suffered unavoidable weight growth. However, NASA officials familiar with the ASRM program counter that even if the ASRMs do not fully achieve their expected performance, their development will eventually lead to more reliable solid rocket motors for the Shuttle.

[14] *Aerospace Safety Advisory Panel Annual Report*, op. cit., footnote 12.

[15] NASA's LRB studies have estimated that development and testing of LRBs would take until 1997. However, recent studies by Rocketdyne and by General Dynamics suggest that LRBs could be purchased more cheaply and developed in less time.

[16] Rocketdyne briefing to OTA, May 3, 1989.

Although Shuttle-C could not carry people, it would be capable of flying some missions that would otherwise require Shuttle flights and could therefore substitute for purchasing an additional orbiter. For example, if Shuttle-C were used to ship major subassemblies of the space station to orbit, one Shuttle-C flight would replace two to three Shuttle missions. According to NASA, four Shuttle-C flights could reduce the number of Shuttle flights necessary to assemble the Phase I Space Station from about 21 to about 10.

Shuttle-C would have the advantage of using much of the same technology and parts that have already proved successful in 28 Shuttle flights. It would use the same launch pads, vertical integration facilities, and launch support crews now used for the Shuttle. It carries the disadvantage that because so many of the proposed Shuttle-C's components are common to the Shuttle, an interruption of Shuttle operations as a result of an accident or technical problem might well lead to delays of Shuttle-C flights for the same reasons. Conversely, a failure of the Shuttle-C would probably ground the Shuttle fleet.

Choosing among these alternatives is very difficult because the choices are constrained by budget limitations as well as competing technical capabilities. If Congress determines that NASA should maintain a Space Station construction schedule offering full operational capability of its first phase by 1998, then any of these options except perhaps LRBs would assist that effort. Improved RSRMs could provide a modest increase in Shuttle payload capability. ASRMs and LRBs may both achieve greater payload weight enhancements for servicing, but LRBs might not be ready in time to be of help in constructing the Space Station on the existing schedule. However, LRBs may offer safer Shuttle launch processing and improvements in safety for Space Station operation, any additional Space Station construction, and for other Space Shuttle missions. NASA officials estimate that the costs of developing the Shuttle-C or the ASRM are roughly equivalent, and that either system could be available by 1995. Shuttle-C would provide the greatest payload improvement, and would reduce much of the pressure of depending on the Shuttle for building the Space Station. However, NASA has identified few payloads for a Shuttle-C beyond the Space Station components.

If Congress decides that the advantages of having the heavy-lift capacity potentially provided by the Shuttle-C, and/or the extra margin of safety and reliability provided by the LRBs outweigh the advantages of developing the ASRMs by 1995, it might wish to reconsider its decision to proceed with ASRMs.

Making major Shuttle enhancements on a project-by-project basis may not be the most efficient way to improve the Shuttle system. To choose one improvement may mean not pursuing another, worthwhile improvement. However, having a versatile, capable launch fleet that provides reliable human access to space will be important if Congress desires to maintain a policy of supporting a human presence in space. Hence, **Congress may wish to consider a more integrated approach to strengthening the Nation's space transportation capability by funding a Shuttle Improvement Program lasting, for example, 10 years.** Such a program could include development of advanced solid rocket boosters, liquid rocket boosters, and the

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[17] U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide, OTA-ISC-383* (Washington, DC: U.S. Government Printing Office, July 1988).

Shuttle-C, as well as additional, more modest, improvements summarized in box 1-A. To support this sort of program, which could cost as much as $850 million per year for 10 years, would require finding extra space program funding, scaling down the Space Station program, or deferring other programs.

RESCUE OR ESCAPE VEHICLES

Crews living and working in the planned Space Station could be exposed to substantial risk from major failures of the Station or the Space Shuttle that transports the crew. NASA is attempting to reduce such risk by building safety features into the Space Station and improving the Shuttle's design. Nevertheless, many analysts in NASA and the broader U.S. space community believe that the United States may need some means independent of the Shuttle to rescue crews from the Space Station. Several options have been suggested (box 1-B); these could be based at the Space Station or on Earth. **To decide whether a risk-reducing effort is worth the investment required, Congress must be advised about how much the investment would reduce the risk. Even if an alternate crew return capability were provided and worked as planned, it would not eliminate all risks to station crewmembers.** A risk assessment of the Space Station should take into account all phases of the crews' experience in space. For example, if the greatest risk to Space Station crew members were experienced in the flight to orbit, it may be more cost-effective to improve the safety of the Shuttle or any later crew-carrying space transportation systems than to build a crew escape craft.

A rescue system, if built, would be needed for the life of the Space Station. Therefore, its total operating costs could easily exceed its development costs. **Before committing to a specific rescue strategy, system designers will have to address the costs of developing the necessary support infrastructure, which might include ground operations hardware and personnel at the mission control site, landing site crews, and the necessary subsystems and logistics support to resupply, replenish, and repair a rescue vehicle on orbit.** Each of these factors can seriously influence the operational characteristics and costs of the system.

Box 1-B—Escape Vehicles

Several contingencies could require emergency escape of personnel in space. These include medical emergencies of Space Station crew members, major equipment failures, damage from orbital debris, etc. Escape could also be necessary if the Shuttle failed to meet its scheduled launch date by so long a time that the Station risked running out of critical supplies.

Crew Emergency Return Vehicles (CERV)

NASA is considering two types of vehicles for emergency return from space to Earth:

- *Capsule*—This simple vehicle would have an ablative heat shield reminiscent of reentry capsules from the early days of spaceflight, and still used routinely by the Soviet Union. A capsule, which could closely resemble the Apollo capsule, would descend by parachute and land in the ocean. Its advantages include simplicity, relatively low cost, and proven technology. In addition, capsules need little or no piloting, which could be a major consideration if pilots are unavailable because they are unable to function as a result of injury or a long stay in orbit. Depending on its capability, a capsule could cost $0.75 billion to $1.0 billion to develop.
- *Small Glider*—A small, aerodynamically stable vehicle whose shape would provide lift, and could land by parachute or at low speed on a runway. A glider would provide a wider range of landing sites and more frequent opportunities for reentry and recovery (particularly for a version with landing gear), and a softer ride than capsules (important if an injured crew member is returning). However, a glider would cost 20 to 50 percent more than the simplest parachute version of a capsule.

NASA is also studying the possibility of building a specialized glider that could be launched into space atop an expendable launch vehicle as well as return from the Space Station. Such a glider could be used to provide 1) crew emergency rescue, 2) assured access to space by crews, 3) small logistics transport, and 4) on-orbit maneuver. Whether capsules or gliders, emergency rescue vehicles could be launched by Titan III and Titan IV by 1995. Alternatively, a Shuttle could launch two at a time, to be docked at the Space Station.

OPTIONS FOR THE NEXT CENTURY

Sometime in the early years of the next century our existing launch systems will wear out or become operationally obsolete. At that point the United States will want to replace them with more advanced systems. NASA and the DoD are considering a variety of options for advanced, crew-carrying launch systems.

Personnel Carrier Launched on Automated Launch Vehicles

NASA is beginning to explore the possibility of developing a personnel launch system (PLS) that would use a small glider launched atop an expendable launch vehicle, rated to carry people.[18] Candidate launchers could include a Titan III or Titan IV, or perhaps a new, as-yet undeveloped launcher such as the Advanced Launch System (ALS).

The ALS Joint Program Office has recognized the potential benefit of having a flexible launch vehicle rated for launching crews. It has therefore required that contractor proposals for an ALS provide for a launch vehicle capable of meeting both the design and quality assurance criteria for crew-rating. Designing an ALS launch vehicle at the outset to provide the additional structural strength for crew-rating would be much less expensive than redesigning, rebuilding, and retesting it after it is developed.

Photo credit: National Aeronautics and Space Administration

Artist's conception of an Apollo-type emergency rescue vehicle entering the Earth's atmosphere after leaving the Space Station.

Having a crew-rated automated launcher in addition to a Shuttle has three strong advantages: 1) the crew-rated vehicle could launch new orbiters designed for launch with other boosters; 2) it could enhance crew safety (if the crew-rated launch vehicle carried an Apollo-like capsule, crew escape could be easier than with the Shuttle, and escape would be possible during more of the trajectory than with the Shuttle); and 3) there may be cases where it will be necessary only to deliver personnel and cargo to the Space Station, but not return cargo on the same trip. In that case, there is no need to risk a Shuttle orbiter. **In view of the concerns over Shuttle fleet attrition, it may be important for NASA to investigate the potential for using a crew-**

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[18] A NASA or Air Force launch vehicle is said to be crew, or "man-rated," if it has been certified as meeting certain safety criteria. These include design criteria as well as quality assurance criteria.

rated ALS or other expendable launcher to reduce the risk of losing crew-carrying capacity early in the next century.

Advanced Manned Launch System (AMLS)

NASA is studying several advanced concepts for vehicles to replace the Shuttle. The Advanced Manned Launch System (AMLS—previously called Shuttle II) program is studying new designs with the goal of achieving an improved U.S. piloted spaceflight capability early in the next century. A vehicle significantly different from the existing Shuttle would result (box 1-C). If activities involving crews in space increase markedly in the next decade, and the Shuttle proves unable to perform its missions, an AMLS using advanced technology[19] might be needed. It could offer significant improvements in operational flexibility and reduced operations costs over the existing Shuttle. However, development, thorough testing, and procurement of an AMLS fleet could cost $20 billion to $30 billion (1989 dollars).

The timing of the development phase for an AMLS would depend on NASA's need to replace the Shuttle fleet. It will also depend in part on progress reached with technologies being explored in the Advanced Launch System and National Aero-Space Plane (NASP) programs. In any event, a decision on AMLS will not have to be made for several more years. For example, if Congress decided that an operational AMLS was needed by 2010, the decision to start the early phases of development would have to be made by about 1995. By that time, Congress should have had adequate opportunity to assess the progress made in the NASP program (see below), which could be competitive with an AMLS.

Box 1-C—Advanced Manned Launch System (AMLS)

The goal of the NASA AMLS program is to define advanced manned launch system concepts, including their development, system and operational characteristics, and technology requirements. A vehicle significantly different from the existing Shuttle would result. NASA is presently evaluating five concepts:

- an expendable in-line two-stage booster with a reusable piloted glider;
- a partially reusable vehicle with a glider atop a core stage;
- a partially reusable drop-tank vehicle similar to the fully reusable concept below but with expendable side-mounted drop tanks;
- a fully reusable rocket with a piloted orbiter parallel-mounted (side-by-side) to an unpiloted glideback booster;
- a two-stage horizontal takeoff and landing air-breather/rocket, which would be fully reusable.

Critical technology needs for all AMLS concepts include:

- light-weight primary structures
- reusable cryogenic propellant tanks
- low-maintenance thermal protection systems
- reusable, low-cost hydrogen propulsion
- electromechanical actuators
- fault tolerant/self-test subsystems
- autonomous flight operations

Building an Aerospace Plane

Developing a reusable vehicle that could be operated like an airplane from conventional runways, but fly to Earth orbit powered by a single propulsion stage would provide a radically different approach to space launch and a major step in U.S. launch capability. However, building such a vehicle poses a much larger technical challenge than building a two-stage, rocket-based AMLS. An aerospace plane could spur the development of two new classes of military aircraft—one that would combine quick response, global ranges, and hypersonic[20] speed with take-off or landing in any part of the world, and another that would combine access to space with quick response from conventional runways.

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[19] The character of technology used in an AMLS would depend on NASA's goals for this launch system and the epoch in which its design was selected. For example, if technologies used for the AMLS were frozen at 1992 levels, they would be considered "near term." However, if a decision to build an AMLS were not reached until the middle of the 1990s, the technologies designers would use to create an AMLS could be far more advanced.

The Department of Defense and NASA are jointly funding the NASP program to build the X-30 (box 1-D),[21] a research vehicle intended to demonstrate both single-stage access to space and endo-atmospheric hypersonic cruise capabilities. **NASP is a high-risk technology development program. Building the X-30 and achieving orbit with a single stage would require major technological advances in materials and structures, propulsion systems, and computer simulation of aerodynamic and aerothermal effects from Mach 1 to Mach 25.**[22] The uncertainties in meeting design goals are compounded because the successful operation of the X-30 would require all of the key enabling technologies to work in concert with one another. In addition, ground test facilities cannot replicate all of the conditions that would be encountered in ascent to orbit. Therefore, it is impossible to predict precisely how the X-30 would perform when pilots make the first attempts to push it far into the hypersonic realm.

As the NASP program is presently structured, it is organized to meet a series of technical and programmatic milestones, rather than a given schedule. However, there is some danger that in the current fiscally constrained environment, the program office might relax some of its own technical criteria in order to meet a schedule. The next major milestone will occur when the NASP program reports on its progress in meeting the Phase II technology development goals. If the NASP program were funded at the level requested in the 1990 budget submission ($427 million), NASP officials estimate they would be ready to decide on development of an X-30 at the end of fiscal year 1990. Program officials estimate that if the program experiences no delays as a result of unanticipated technical problems or of budgetary cuts, an X-30 begun in fiscal year 1991 could achieve orbital spaceflight by October 1996.

Box 1-D—What Is the National Aero-Space Plane Program?

NASP is a program to build the **X-30**, an experimental, hydrogen-fueled, piloted aerospace plane capable of taking off and landing horizontally and reaching Earth orbit with a single propulsion stage. The design of the X-30 would incorporate advanced propulsion, materials, avionics, and control systems, and make unprecedented use of supercomputers as a design aid and complement to ground test facilities. NASP is a technically risky program that could spur the development of a revolutionary class of reusable, rapid turn-around hypersonic flight vehicles, that would be propelled primarily by air-breathing "scramjet" engines.

Operational follow-ons to the X-30: An aerospace plane derived from NASP technology offers the promise of dramatically reduced launch costs if the vehicle can truly be operated like an airplane using standard runways, with minimum refurbishing and maintenance between flights.

The X-30 would be a research vehicle, not a prototype of an operational vehicle. To develop an operational vehicle would require an additional, costly program beyond NASP. A development cycle that took full advantage of lessons learned in the X-30's planned test program could not commence until the late 1990s at the earliest. An operational vehicle derived from the

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[20] Mach 1 is the speed of sound. *Hypersonic* usually refers to flight at speeds of at least Mach 5—five times the speed of sound, or about 4,000 miles per hour.

[21] However, a recent decision to cut the proposed DoD contribution to NASP funding by two-thirds for fiscal year 1990 and to terminate funding for it in subsequent years puts the program in doubt. See later discussion in this section.

[22] Mach 25 (25 times Mach 1), is the speed necessary to reach Earth orbit.

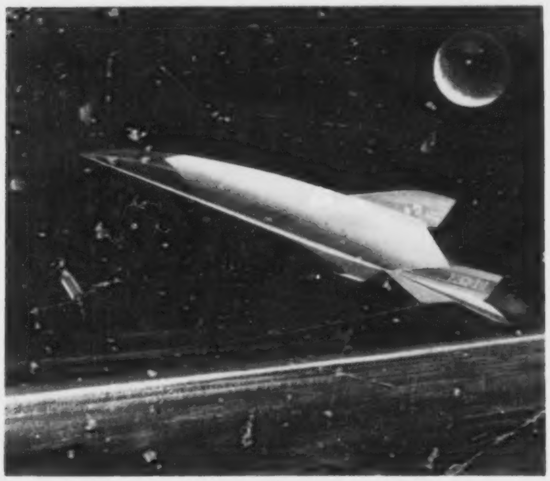

Photo credit: McDonnell Douglas

Artist's conception of an X-30 aerospace plane.

proposed X-30 would therefore be unlikely until approximately 2005 or even later unless it were closely modeled on the X-30.

If the X-30 proved successful, the first operational vehicles that employ NASP technologies are likely to be built for military use, possibly followed by civilian space vehicles. Commercial hypersonic transports (the "Orient Express") are a more distant possibility. Recent studies have shown that from an economic standpoint, commercial hypersonic transports compare unfavorably with proposals for slower Mach 3 supersonic transports based on less exotic technology and conventional fuels. Therefore, **the most economic route to commercial high-speed air transport is unlikely to be through the X-30 development program. However, the X-30 program could provide technical spin-offs to aerospace and other high-technology industries through its development of advanced materials and structures and through advances in computation and numerical simulation techniques.** It is too early to judge the economic importance of such spinoffs.

Operational hypersonic aircraft and spaceplanes may raise concerns about their effect on Earth's atmosphere. Designers are hopeful that vehicles that cruise well above the stratospheric ozone layer, and whose combustion products are mostly water vapor, will not affect the environment significantly. The NASP program office is sponsoring research on the potential atmospheric effects of a fleet of follow-on vehicles to give a preliminary assessment of the major environmental questions.

Even assuming a rapid resolution of the myriad of technical issues facing the creation of an X-30 capable of reaching orbit with a single propulsion stage, translating this technology into an operational spaceplane might come late in the period when an AMLS could be ready, and perhaps after the time when replacements for the Shuttle will be necessary. With their less exotic technologies, rocket-propelled AMLS vehicles could probably be funded in the mid to late 1990s and still be developed in time to replace aging Shuttles. An AMLS program begun in this period would also benefit from the technical base being developed in the NASP program. **However, the technical uncertainties of both programs suggest that Congress would benefit from monitoring their progress and comparing the probability of success of each before committing development funds for operational vehicles in the mid-1990s. The costs of each program, as well as other competing budget priorities, will play a major role in such a decision.**

The revised DoD budget of April 1989 would cut DoD fiscal year 1990 funding for NASP from $300 million to $100 million. DoD would contribute no funds in subsequent years. DoD has also proposed transfering responsibility for managing NASP from DoD to NASA and allowing NASA to obligate the $100 million of fiscal year 1990 DoD funds.

The proposed cuts and change of management have raised the concerns of NASP proponents and accelerated a review of the NASP program. Many of the ongoing research efforts on materials, structures, and propulsion design, which would be needed to support an informed decision on the technical feasibility of building an X-30, are scheduled for completion in fiscal year 1990, the last year of Phase II. Furthermore, critical applications and cost studies are not yet complete.

Congress has three broad options on NASP funding:

- **Continue to fund the program at or near the original requested rate ($427 million).** Funding of this level would allow the NASP program to continue its Phase II research program and to complete its application and cost studies by the end of fiscal year 1990. At that point, the Administration and Congress could then decide whether or not to build two X-30 test vehicles, as planned.

  If the NASP program receives a budget cut, and the joint management arrangement is maintained, the Phase III decision would likely slip by a year or more, depending on the size of the cut. Although the program would then risk losing momentum and industry support, stretching Phase II out but retaining total funding of roughly $427 million would still allow the program to reduce many of the current uncertainties in the technology.
- **Accept the current DoD proposal for program cuts and transfer the program to NASA.** Under this option, the NASP program would still be able to pursue useful technology studies. However, the focus of the program would change to emphasize the maturation of critical technologies in lieu of building a flight vehicle. In addition, a decision whether or not to construct a flight vehicle might be delayed two or more years. If managed by NASA, the program would compete with funding for alternative launch systems such as the AMLS and also with the Space Station program, which, along with Space Shuttle, will command most of NASA's resources for the next decade and more.[23]

  Moreover, a decision to transfer the program to NASA with only limited funding would delay a decision on whether to build a flight vehicle by several years. In the interim, the Nation might risk losing the substantial technology base that the NASP program has built for hypersonic flight. Recreating this technological base would be both costly and time consuming.
- **Close out the NASP program.** If Congress feels that the long-term goals of the NASP Program are less important than other pressing priorities in the Federal budget, it could terminate funding entirely. However, much of the progress made in the program would be lost because contractors would not be able to continue their research to a logical conclusion.

SPACE TRANSPORTATION AND THE SPACE STATION

NASA's planned Space Station will make permanent demands on space transportation—for construction, servicing, supply, and possibly emergency crew return. **Uncertainty about the adequacy of the current Shuttle fleet for constructing and servicing the Space Station makes station planning itself both uncertain and risky. Deployment, servicing, and resupply of the Space Station face both the risks of delayed launch schedules and loss of one or more orbiters. In addition, losing a critical element of the Space Station in transit to orbit as a result of a Shuttle failure could lead**

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[23] U.S. Congress, Congressional Budget Office, *The NASA Program in the 1990s and Beyond* (Washington, DC: Congressional Budget Office, May 1988).

to severe delays in Space Station construction or even loss of the Space Station.[24]

A previous section outlined options for reducing the space transportation risk to Space Station construction and operation. However, most of these options would require additional funding beyond NASA's projected budget for Space Station or for space transportation. **Congress may wish to postpone Space Station construction and operation and focus on improving the Nation's ability to place crews in orbit safely and reliably. Alternatively, Congress could direct NASA to fly fewer non-Space Station-related Shuttle missions in order to reduce the risk that a Shuttle would be lost before Space Station construction is completed.** NASA might, for example, plan to use Titan IVs to carry some Space Station elements into orbit rather than risking the Shuttle to do so. Furthermore, if appropriately designed, many science payloads now tentatively manifested for the Shuttle could be flown on ELVs purchased competitively from the private sector.[25]

THE TECHNOLOGY BASE FOR PILOTED SPACEFLIGHT

Building a new, advanced launch system, or even making substantial modifications to existing launchers, requires a capable aerospace industry, well-supported government research programs, a cadre of well-trained engineers, and an institutional structure capable of putting a vast variety of technologies to innovative use. Yet, according to several recent studies, our existing space technology base has become inadequate in recent years.[26]

Government Programs

Several of these studies have recommended improving the Nation's space transportation technology base. Though specific proposals differ in detail, they cite propulsion, space power, materials, structures, and information systems as areas in need of special attention.

In response to these and other concerns, NASA and the Air Force have initiated four major programs to improve the Nation's launch system technology base (box 1-E). As currently organized, these programs are directed primarily toward developing new, advanced capabilities. **In the existing budget climate, it may be more realistic to redirect some funding toward technologies that could be used to improve existing launch systems and make them cheaper to operate.** Several launch vehicle manufacturers have already instituted programs to improve their launch vehicles, based on technologies developed for the Advanced Launch System program.

As noted in *Reducing Launch Operations Costs: New Technologies and Practices*, launch operations and logistics, especially for systems that carry people, are labor-intensive and comprise a significant percentage of the cost of a launch. Yet launch system designers have invested relatively little in technologies that would reduce these costs. NASA's technology programs are addressing issues in automation and robotics, two technology areas that could significantly reduce launch operations costs. However, NASA could do much more to apply these technologies to launch operations for the Shuttle. **Funding basic and focused research for space transportation technologies would help**

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[24] If a Space Station element for which there was no spare were lost, replacing that element would take many months.

[25] Current space policy requires NASA, "to the maximum extent feasible," to purchase expendable launch vehicle services competitively from private launch companies—The White House, Office of the Press Secretary, "Presidential Directive on National Space Policy," Fact Sheet, February 11, 1988, p. 9.

[26] See, for example, National Research Council, Aeronautics and Space Engineering Board, *Space Technology to Meet Future Needs* (Washington, DC: National Academy Press, December 1987); National Commission on Space, *Pioneering the Space Frontier* (New York: Bantam Books, May 1986); National Aeronautics and Space Administration, *Leadership and America's Future in Space* (Washington, DC: NASA, August 1987).

Box 1-E—Government Space Technology Programs

- *Advanced Launch System (ALS) Focused Technology Program*—a joint program between NASA and the Air Force, carried out as an integral part of the ALS Demonstration/Validation Program. Its aim is to pursue research on specific technologies of interest to the development of an ALS. The program's contribution to crew-carrying capabilities will be limited, but important. As much as possible, ALS program managers have deliberately targeted their research at generic space transportation issues, in order to develop a broad technology base for designing an ALS. The ALS program plans to spend $81.4 million on focused technology R&D in fiscal year '89, out of a total budget of $153 million.
- *Civil Space Technology Initiative*—a NASA program designed to revitalize "the Nation's civil space technology capabilities and enable more efficient, reliable, and less costly space transportation and Earth orbit operations."[1] Funding for fiscal year '89 is $121.8 million ('90 request—$144.5 million).
- *National Aero-Space Plane*—a DoD/NASA program to develop an aerospace plane capable of reaching orbit with a single propulsion stage. Although this program does not have the specific focus of improving the Nation's technology base, some of the technology under development necessary for building the NASP, particularly new materials and structures, new propulsion techniques, new computational techniques, and methods of handling liquid and slush hydrogen, will find application elsewhere. The NASP Joint Program Office is spending $150 million over a 30-month period on materials development alone.
- *Pathfinder*—a NASA program especially directed at technologies for future human space exploration. Funding for fiscal year '89 is $40 million (fiscal year '90 request $47.3 million). Very few of this program's technologies will be useful for Earth-to-orbit transportation, as it is directed primarily toward on-orbit and interplanetary transportation and life-support issues.

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[1] National Aeronautics and Space Administration, Office of Aeronautics and Space Technology, "CSTI Overview," April 1988.

the United States prepare to meet future space transportation needs.

The Private Sector Role

In providing space transportation for people, private firms now serve primarily as contractors for government-defined needs. Reaching orbit and working in space requires so large an investment compared to the expected return that private firms are unlikely to take the initiative in developing crew-related space systems unless Congress and the Administration set a high priority on involving them more directly in such development.[27] Because the government controls both access to space and most of the technology, it will continue to determine launch specifications and provide most of the funding. This is especially true for systems involving crews in space, in large part because such systems are still in the early stages of development, but also because they represent a major national commitment and are funded solely by public money.

By promoting private sector innovation toward improving the design, manufacture, and operations of launch systems, the government could reduce the cost of government launches. Yet relatively few incentives to involve private firms exist today.

If technology for crew-related systems eventually becomes an important arena for private investment, commercial pressures will themselves provide the incentives for launch system innovation. For the near term, however, such incentives must come from the government because projected future demand for crew-carrying space transportation is small and depends entirely on government specifications.[28]

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[27] The NASP program, for example, has set a high priority on directly involving private firms and universities in materials research and other advanced research on the X-30.

Incentives provided by the government could include:

- direct grants to develop new technology for launch systems specifically directed toward saving costs rather than increasing performance;
- cash incentives to firms for reducing the manufacturing costs of specific items procured by the government;[29]
- encouragement of industrial teaming arrangements such as the NASP Materials Consortium.

INTERNATIONAL COMPETITION AND COOPERATION

Competition

This decade has seen the rise of international competition in space transportation. The development of space transportation systems is the major achievement that signals a nation's or region's status as a space power, able to develop and control the use of advanced technology. In addition to the Soviet Union, Europe, Japan, and China now operate systems capable of launching sizable payloads.

At present, only the United States and the Soviet Union are able to send humans to and from space. However, the European Space Agency (ESA), the Federal Republic of Germany, Japan, and the United Kingdom are all developing their own reusable or partially reusable launch systems, which, if successful, would be capable of transporting human crews. **The progress other countries are making in space transportation for human crews is likely to present technological and political challenges to the United States by the end of the century.**

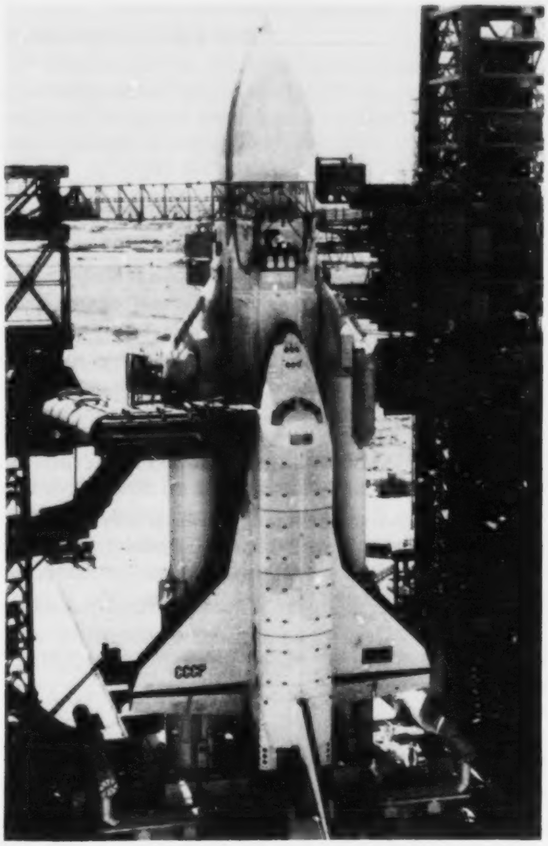
Photo credit: Novosti

Soviet Shuttle *Buran* on the launch pad at the Soviet launch complex.

Cooperation

The United States has always maintained a vigorous program of international cooperation in space science and applications in order to support U.S. political and economic goals. However, it has cooperated very little with other countries in space transportation, in part because most launch technology has direct military applications and is therefore tightly controlled. **Nevertheless, because other countries have**

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[28] Richard Brackeen, *Space Challenge '88: Fourth Annual Space Symposium Proceedings Report* (Colorado Springs, CO: U.S. Space Foundation, 1988), pp. 76- 79.

[29] For example, Rockwell International earns 20 percent of every dollar it saves NASA on building Shuttle orbiter OV-105.

developed their own launch capability, reducing much of the technological lead the United States once held, and because progress in space will continue to be expensive, cooperating on new space transportation systems could benefit the United States.

For example, the United States has a strong need to reduce the number of Shuttle flights needed to construct and resupply the Space Station. It could benefit by sharing responsibility for resupply of the Space Station with its Space Station partners. ESA and NASA have now established a working committee to discuss appropriate standards for packaging, docking, and safety. If such cooperation proves successful, it could be extended to include more sensitive aspects of space transportation. In particular, because ESA and Japan have developed and now operate their own launch systems, they may have specific technologies or methods to share with the United States in return for access to some U.S. technology.

The United States could even be more innovative in cooperating with other countries. For instance, the United States may decide to provide an emergency crew escape or return vehicle for the Space Station. NASA estimates that the development of such a vehicle would cost between $0.75 billion and $1.50 billion, depending on its level of sophistication. **If properly redesigned and outfitted, the European spaceplane, *Hermes*, might be used as an emergency return vehicle.** *Hermes* could even complement the Shuttle in Space Station crew rotation. However, this option would require radical change in U.S. thinking about Space Station crew rescue and a similiar change in *Hermes* planning as well. Specifically, it would require partial redesign of *Hermes* to carry more than the three crew members now planned for this space plane. It would also require a degree of international cooperation for which the United States has little precedent.

Photo credit: British Aerospace

Artist's conception of British Aerospace's Hotol aerospace plane taking off. If successful, this space plane would reach Earth orbit with a single propulsion stage.

Because of the proprietary and military nature of space transportation technology, cooperation in this area can be expected to be more difficult than cooperation in space science. Yet the United States engages in a variety of cooperative projects for the development of military systems. A deeper commitment to international cooperation would assist the United States in achieving much more in space than it can afford to attempt on its own. To do this will require that NASA and the U.S. aerospace industry do much more to tap the technologies and expertise available in other industrialized countries.

Chapter 2

Issues and Options

Photo credit: National Aeronautics and Space Administration

Space Shuttle *Challenger* lifts off from Kennedy Space Center on its second flight, June 18, 1983.

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Chapter 2

Issues and Options

The United States today depends entirely on the Space Shuttle for transporting crews to and from space. Not only does the Shuttle function as a vehicle for launching spacecraft, it also serves as a platform for experiments in science and engineering. In the future, NASA intends to use the Space Shuttle to deploy and service the planned Space Station. As the Nation looks toward the future of piloted spaceflight, it may wish to improve the Shuttle's reliability, performance, and operational efficiency. Eventually, additions to the Shuttle fleet or replacement Shuttles will likely be desirable. This chapter summarizes the major issues of maintaining and improving the Space Shuttle and developing advanced crew-carrying launchers. It also presents a range of congressional options for responding to these issues.

LAUNCHING HUMANS TO SPACE

One of the distinguishing characteristics of the U.S. civilian space program is its emphasis on people in space, to demonstrate U.S. leadership in the development and application of high technology. Since the early days of the Apollo program, the "manned" space efforts of the National Aeronautics and Space Administration (NASA) have served as a major driver of the direction and spending of its space activities. Today, NASA's projects involving people in space, primarily the Space Shuttle and Space Station programs, consume between 65 and 70 percent of NASA's budget (table 2-1).

Critics of NASA's emphasis on humans in space, especially critics in the space science community, have questioned the wisdom of continuing to emphasize these activities because of the heavy explicit and implicit demands they place on the civilian space budget. In particular, critics note that using the Shuttle to launch the Hubble Space Telescope and large solar system probes, like Galileo and Ulysses, subjects space science to unnecessary reliance on the Shuttle's ability to meet a launch schedule.[1] These critics point out that Europe and Japan, while spending considerably less on space than the United States, have nevertheless achieved noteworthy scientific and technological results. However, supporters of maintaining the human presence in space argue that such activities provide essential visibility for the U.S. space program and underscore America's international technological leadership:

> The [manned] space[flight] program is a visible symbol of U.S. world leadership; its challenges and accomplishments motivate scientific and technical excellence among U.S. students; and it provides for a diverse American population a sense of common national accomplishment and shared pride in American achievement.[2]

Current space policy calls for demonstrating U.S. leadership by expanding "human presence and activity beyond Earth orbit into the solar system," and "continuing our national commitment to a permanently manned Space Station."[3] U.S. space policy directs NASA to improve the Space Shuttle system and start the Space Station by the mid-1990s. It also directs NASA to establish sustainable Shuttle flight rates for use in planning and budgeting Government space programs, and to pursue appropriate enhancements to Shuttle operational capabilities, upper stages, and systems for deploying, servicing, and retrieving spacecraft as national requirements are defined.[4]

Achieving all of these goals would be expensive. In the Apollo era, the Nation had the well-defined political goal to land a man on the Moon within a decade and return him, a goal that carried the rest of the space program and a large budget commitment with it. If the budget for space activities were unlimited and if the needs of the various space interests could all be met equally well, then many space program goals might be usefully pursued at the same time. The United States could maintain its

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[1] Robert Bless, "Space Science: What's Wrong at NASA," *Issues in Science and Technology*, winter 1988-89, pp. 67-73; Bruce Murray, "Civilian Space: In Search of Presidential Goals," *Issues in Science and Technology*, spring 1986, pp. 25- 37.

[2] John M. Logsdon, "A Sustainable Rationale for Manned Space Flight," *Space Policy*, vol. 5, 1989, pp. 3-6.

[3] The White House, Office of the Press Secretary, "The President's Space Policy and Commercial Space Initiative to Begin the Next Century," Fact Sheet, Feb. 11, 1989.

[4] Ibid.

Table 2-1—National Aeronautics and Space Administration Fiscal Year 1990 Budget Summary for Space[a] (millions of current-year dollars)

	Budget Plan		
	1988	1989	1990
Research and Development	**2,922.0**	**3,862.4**	**5,288.8**
Space Station	392.3	900.0	2,050.2
Space transportation capability development	593.4	681.0	639.0
Space science and applications	1,581.8	1,830.2	1,995.3
Technology utilization	19.0	16.5	22.7
Commercial use of space	29.7	28.2	38.3
Transatmospheric research and technology	52.5	69.4	127.0
Space research and technology	221.3	295.9	338.1
Safety, reliability, and quality assurance	14.1	22.4	23.3
University space science and technology academic program	(21.6)	(22.3)	35.0
Tracking and data advanced systems	17.9	18.8	19.9
Space Flight, Control, and Data Communications	**3,805.7**	**4,464.2**	**5,139.6**
Shuttle production and capability	1,092.7	1,128.2	1,305.3
Space transportation operations	1,833.6	2,390.7	2,732.2
Space and ground networks communications and data systems	879.4	945.3	1,102.1
Construction of Facilities	**178.3**	**275.1**	**341.8**
Research and Program Management	**1,762.2**	**1,891.6**	**2,032.2**
Total Budget Summary	**9,001.1**	**10,493.3**	**12,804.4**

[a] Total NASA budget less aeronautical research & technology

SOURCE: National Aeronautics and Space Administration.

preeminence in space transportation as well as in other space activities. However, as a result of the current budget stringency, Congress must choose among competing ideas for the United States to demonstrate its leadership rather than attempting to demonstrate leadership across the board.

In contrast to U.S. civilian activities, the military space program has spent relatively little on crews in space, despite numerous efforts over the years by some to identify military missions that would require crews. Indeed, DoD has recently reaffirmed that it has no requirements for crews in space. Production of a piloted aerospace plane for military use, such as is contemplated for a follow-on to the current National Aero-Space Plane Program, would reverse this historical stance.

An assessment of the appropriate mix of crew-carrying and robotic efforts for space science and exploration, or for military activities, is beyond the scope of this study. Expanded commitment to crews in space, as contemplated by NASA and the Air Force, would require increasing budgetary outlays and would likely require the development of new and costly crew-carrying space vehicles.

To illustrate the problem Congress faces, the Space Shuttle system and the Space Station, both of which require crews, dominate NASA's budget for the 1990s.[5] As noted in a 1988 Congressional Budget Office report, simply to maintain NASA's "core program," which includes these major programs, but no large additional ones, will require NASA's overall budget to grow from $10.5 billion in fiscal year 1989 to about $14.4 billion in fiscal year 1995.[6] NASA plans to spend about $2.5 billion per year for investment in its space transportation system, including improvements to the Shuttle, an advanced solid rocket motor, and in-orbit transportation vehicles. Operating the Shuttle will cost an additional $2.0 billion. Anything new, such as an additional orbiter beyond OV-105, major modifications to the Shuttle, a Shuttle-C, a Personnel Launch System, or a crew return vehicle, will add to these costs.

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[5] Most of President Bush's 20 percent suggested budget increase for NASA for fiscal year 1990 derives from increases to build the Space Station, which is scheduled for permanent occupation in 1996.

[6] U.S. Congress, Congressional Budget Office, *The NASA Program in the 1990s and Beyond* (Washington, DC: May 1988), pp. x-xiv.

Spaceflight is inherently risky. As noted in the next section and in chapter 3, the exact reliability of the Shuttle system is uncertain, but experts suggest it ranges between 97 and 99 percent. Therefore, the United States may expect to lose or severely damage one or more orbiters within the next decade, perhaps with loss of life. As America's reaction to the *Challenger* disaster demonstrated, the loss of another Shuttle crew in addition to an orbiter would likely result in another long standdown of the Space Shuttle system and could sharply reduce the productivity of the civilian space program. Loss of an orbiter would also certainly lead to a painful reexamination of the space program's purpose and direction.

One of the major challenges for the U.S. civilian space program will be to learn how to reconcile America's goals for the expansion of human presence in space with the ever present potential for loss of life. **In particular, if the United States wishes to send people into space on a routine basis, the Nation will have to accept the risks these activities entail. If such risks are perceived to be too high, the Nation may wish to reduce its emphasis on placing humans in space.**

DEPENDENCE ON THE SPACE SHUTTLE

U.S. dependence on the Space Shuttle for carrying crews to space raises questions concerning the longevity of the Shuttle fleet and the risks that orbiters might be unavailable when needed. These involve the inflexibility of the Shuttle system, especially when scheduled to fly at rates close to the maximum projected sustainable flight rate, and possible attrition of the Shuttle fleet.

Inflexibility

Although NASA has estimated that Kennedy Space Center can launch at most 14 Shuttles per year with existing facilities,[7] NASA has scheduled 14 Shuttle flights in 1993,[8] and plans to launch approximately 14 per year through the end of the century. Scheduling launches at the maximum sustainable launch rate leaves no margin to accommodate a sudden change in launch plans or to fly any missions that may be delayed by a future accident.

Attrition

Whatever the launch rate, the fleet will be subject to a growing cumulative risk of attrition.[9] In 1988, a NASA contractor predicted post-*Challenger* Shuttle reliability would be between 97 and 98.6 percent and used 98 percent as a representative estimate.[10] A more recent NASA study estimated the chance of success on the Galileo mission would probably be between 1 in 36 (97.2 percent) and 1 in 168 (99.4 percent).[11] The probability of orbiter recovery after the Galileo mission would be comparable, because the most likely causes of a mission failure would probably destroy the orbiter. **If reliability is and remains 98 percent, there would be a 50 percent chance of losing an orbiter on the next 34 flights,** a 72 percent chance of losing an orbiter before the first Space Station assembly flight (if scheduled for flight 92), and an 88 percent chance of losing an orbiter before Space Station assembly is completed 42 flights later.

Because the construction of additional orbiters requires about 6 years, in the early 1990s the only way to increase the margin in the Shuttle launch schedule is to delay some missions already scheduled or launch them on expendable launchers. **To increase the probability that the Nation will have four operational orbiters in the mid-1990s, when NASA expects to start construction of the Space Station, some missions now scheduled could be**

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[7] Enclosure to letter from Darrell R. Branscome, NASA HQ, to Richard DalBello, OTA, Mar. 31, 1988. A National Research Council panel estimated that only 11 to 13 launches per year could be sustained. See *Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization* (Washington, DC: National Academy Press, October 1986), p. 15.

[8] NASA Headquarters, Transportation Services Office, *Payload Flight Assignments, NASA Mixed Fleet*, June 1989.

[9] Viz. of not recovering an orbiter in refurbishable condition. This may differ from the risk faced by the crew, because the crew might escape in some situations in which the orbiter would be lost.

[10] L-Systems, Inc., *Shuttle/Shuttle-C Operations, Risks, and Cost Analyses*, LSYS-88-008 (El Segundo, CA: L-Systems, Inc., 1988).

[11] NASA, Code Q, *Independent Assessment of Shuttle Accident Scenario Probabilities for the Galileo Mission*, vol. 1, April 1989.

cancelled, delayed, or flown on expendable launchers. Ordering one or more orbiters now would increase the probability of having four operational orbiters after the mid-1990s. Unless additional orbiters are added to the fleet, attrition is likely to decrease fleet size, perhaps much more rapidly than NASA expected originally or now plans for (see ch. 3).

Wearout and Obsolescence

As time goes on, structural fatigue, wearout, and obsolescence will become more important. Existing Shuttle orbiters will be at least 15 years old in the mid-1990s, when Space Station operations are scheduled to begin. By that time, the designs of many Shuttle systems will be 25 years old. It will be economical to replace some systems, such as the Shuttle computers, before they wear out, because redesigned systems may be so much less expensive to maintain and operate that the cost of upgrading would be justified.[12]

Eventually, it will be economical to replace the entire orbiter fleet with a fleet of newly designed vehicles. As discussed in more detail in chapter 3, NASA is now estimating the costs of operating improved Shuttle orbiters and newly designed vehicles that would be used in an Advanced Manned Launch System (AMLS).

NASA, the Air Force, and their contractors are also estimating the costs of operating spaceplanes that could be built using technology to be demonstrated by the experimental X-30 spaceplane now being designed in the National Aero-Space Plane program. When these estimates are completed, comparisons of cost-effectiveness must be made to forecast economic dates for phasing out orbiters of existing design and introducing improved orbiters, an Advanced Manned Launch System, and/or operational spaceplanes incorporating X-30 technology.

IMMINENT DECISIONS

If the United States wishes to continue its strong dependence on the Space Shuttle, decisions about whether or not to purchase a new orbiter or to improve the Space Shuttle system should be be made in the next year or two. These issues are discussed in greater detail in chapter 3.

Order More Orbiters?

The United States must decide soon whether to order one or more Shuttle orbiters in addition to the one (OV-105) now under construction. Buying more orbiters would provide increased fleet capacity and flexibility and compensate for attrition. A new orbiter could be a copy of OV-105, or could be upgraded to improve safety, payload capability, endurance in orbit, or ease or economy of operation. It could be given a capability to fly automatically, with or without a crew aboard, like the Soviet space shuttle.

The longer a decision to order a "ship set" of spare parts or another orbiter is delayed, the greater will be the risk that the tooling or expertise needed to manufacture some parts will be lost, thereby leading to even longer lead times and greater cost.

Improve Existing Orbiters?

Existing Shuttle orbiters and OV-105 could be modified to have some, but not all, of the improvements of safety, payload capacity, endurance, economy, and operability that a new orbiter could have. This option could be chosen whether or not a new orbiter (beyond OV-105) is ordered. It would temporarily reduce the Shuttle flight rate, as making modifications to orbiters effectively removes them from the fleet for several months at a time.

Improve Other Shuttle Elements and Facilities?

Shuttle elements other than orbiters could also be upgraded. NASA and industry are considering many options, with several goals. Some options, for example, would increase the payload a Shuttle could carry to orbit. This would allow the Space Station to be assembled with fewer Shuttle flights and with less extra-vehicular activity (EVA) by astronauts; EVA is risky. It would also allow other payloads to be carried with fewer Shuttle flights, and it would allow heavier payloads to be carried on Shuttle flights.

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[12] NASA has embarked on a program to replace the orbiters'computers. However, because of the pace of improvements in computer technology, by the time they are installed in the early 1990s, these computers will not be state-of-the-art.

These options include:

- continued development of Advanced Solid Rocket Motors (ASRMs),
- modification of Redesigned Solid Rocket Motors (RSRMs) to increase their thrust,
- development of Liquid-fuel Rocket Boosters (LRBs), and
- development of lightweight External Tanks (ETs).

These would increase Shuttle payload capability by different amounts, and their other benefits and dates of availability would differ (see ch. 3). Therefore, two or more options might be pursued.

Alternatively, or in addition, NASA could develop complementary vehicles (e.g., Shuttle-C) to carry large payloads to orbit and reduce the Shuttle flight rate, thereby reducing the risk of Shuttle fleet attrition. The United States need not decide this year whether to proceed with one or more of these options. However, if such improvements are desired, more benefit will be reaped if they are begun sooner rather than later.

Develop Capsules or Gliders for Escape or Rescue?

Space Station crewmembers might become ill or be injured and need to return to Earth before a Shuttle could be prepared to rescue them. Although NASA's Aerospace Safety Advisory Panel has recommended that "a single-purpose crew rescue vehicle or lifeboat should be an essential part of the Space Station's design,"[13] and although NASA's guidelines for "man-rating" space systems require the Space Station to have some sort of escape system (not necessarily single-purpose),[14] NASA has not yet decided to provide an escape system for the Space Station. NASA has not estimated the risk Station crewmembers will face, nor how much it could be reduced by the various escape systems NASA has considered developing.[15] Whatever the risk, it could be reduced to some degree, but not eliminated, by providing an escape system for the Space Station to complement safety measures already being pursued by NASA.[16]

NASA has considered several options for Space Station "lifeboats" (see ch. 6):

- a dedicated Shuttle orbiter docked to the Station;
- Apollo-like capsules; or
- gliders.

After the year 2000, NASA might rely on spacecraft being developed by foreign partners in the Space Station program (*Hermes*, HOPE, *Saenger*, or possibly Hotol), or on "NASP-derived" spaceplanes for crew rescue or escape. But these would not be available for the first years of Space Station operation, unless Space Station construction is delayed.

FUTURE DECISIONS

The United States need not decide now whether to develop an Advanced Manned Launch System along the lines now envisioned by NASA, or some other version, and whether to develop a single-stage-to-orbit aerospace plane. NASA and the Air Force have programs to develop technologies for such vehicles and to estimate their operational capabilities and costs. Industry is also advancing proposals. More technology development, design, and cost/benefit estimation must be done before an informed rational choice can be made in the early to mid-1990s.

Develop the Advanced Manned Launch System or a Different Advanced Rocket?

In its AMLS program, NASA is studying concepts for an advanced reusable crew-carrying orbiter (previously called Shuttle II) to succeed the Shuttle in 2005 or later. NASA is evaluating five concepts:

- an expendable two-stage rocket;
- a partially reusable rocket;
- a partially reusable "drop-tank" rocket;
- a fully reusable rocket; or
- a fully reusable two-stage vehicle that uses airbreathing engines for the first stage.

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[13] Aerospace Safety Advisory Panel, *Annual Report* (Washington, DC: NASA Headquarters, Code Q-1, March 1989), p. 7.

[14] National Aeronautics and Space Administration, *Guidelines for Man-Rating Space Systems*, JSC-23211, preliminary, September 1988.

[15] NASA has not routinely carried out quantitative risk assessments of its systems. See Trudy E. Bell and Karl Esch, "The Space Shuttle: A Case of Subjective Engineering," *IEEE Spectrum*, June 1989, pp. 42-46.

[16] U.S. Congress, Congressional Budget Office, *The NASA Program in the 1990s and Beyond* (Washington, DC: May 1988), pp. x-xiv.

The airbreathing vehicle would take off from a runway like an airplane, and both the unpiloted first stage and the piloted orbiter would land on a runway.

The program will compare the costs and benefits of an AMLS with the Shuttle evolution option under study by the Johnson Space Center. It would be prudent to defer a decision until NASA has completed preliminary designs of alternative vehicles in sufficient detail to estimate technological risk and life-cycle cost.

Develop a Single-Stage-to-Orbit Spaceplane?

The National Aero-Space Plane (NASP) program is designing and developing technology for an experimental single-stage-to-orbit air-breathing jet/rocket aerospace plane, the X-30. Two X-30s are to be built; they are intended to demonstrate the feasibility of taking off from a runway, entering orbit, reentering the atmosphere, landing on a runway, and being prepared for another sortie within 24 hours. If the X-30 is successful, the government will have a basis for greater confidence that operational aerospace planes ("NASP-derived vehicles," or NDVs) of similar design could be built to perform civilian and military missions, including space transportation. An NDV might serve as a space taxi between Earth and low orbit.

The value of NDVs for space transportation will depend in part on the importance of their unique capabilities (e.g., rapid turnaround[17]) and in part on the average cost per flight and per pound of payload. NDVs might be very economical compared to existing launch vehicles, and may compete in cost with the proposed Advanced Launch System (ALS). The NASP Joint Program Office is assessing the ability of NDVs to satisfy some of the Air Force needs[18] that the ALS is being developed to satisfy. However, in contrast to the ALS, a practical NDV would not be able to carry extremely heavy payloads (100,000 to 160,000 pounds to a low-altitude polar orbit).[19]

Average cost would likely depend sensitively on maintenance man-hours per sortie (which is related to turnaround time) and useful life. Aircraft that push technology to the limit to increase speed and altitude to perform novel missions often have greater-than-predicted operating cost and shorter-than-predicted useful life (see ch. 5). The A-11, SR-71, and the Space Shuttle programs illustrated that maintenance man-hours per sortie for such aircraft cannot be estimated with confidence before considerable operational experience has been obtained, and useful life cannot be estimated with confidence before several vehicles have been retired or lost by attrition.

Even if NDVs were more costly than ALS for space transportation, they could be judged worthwhile if they are necessary or uniquely economical for military missions, such as surveillance from orbit. The NASP Joint Program is assessing the ability of NDVs to satisfy needs for a military aerospace vehicle for the Air Force Space Command and a military space flight capability for the Strategic Air Command.

The value and urgency of meeting these needs is difficult to quantify; earlier stated needs for military spaceplanes have gone unmet, with debatable but not catastrophic effect on national security. For example, in 1958 the Air Force proposed development of a rocket-powered spaceplane, the Dyna-Soar. It was to include "a manned capsule with glide interceptor and satellite interceptor, together with global reconnaissance and global bombardment subsystems." The global bombardment capability was to augment the Atlas, Titan, and Thor missiles then in development. The Air Force Deputy Chief of Staff for Development wrote that the Dyna-Soar and four other proposed space programs, including a Lunar Base System and an Advanced Reconnaissance System with a crew-carrying space station, were "essential to the maintenance of our national position and prestige."[20] Development of the Dyna-Soar was approved, but in 1963, halfway through the program, Secretary of Defense Robert McNamara canceled the program, arguing that its objectives could be met with the Manned Orbital Laboratory, which was then just beginning and was later canceled.[21] The value of NDVs will have to be weighed against the ability of other systems to accomplish the Nation's requirements for space transportation.

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[17] "Turnaround time" is the time between a landing and the next take-off of the same vehicle.

[18] Air Force Space Command, *AFSPACECOM Statement of Operational Need (SON) 005- 88 for an Advanced Launch System (ALS)*, Aug. 12, 1988.

[19] In forthcoming analyses of the potential economic benefits of NDVs and the ALS, it will be important to note whether, in estimating the savings achievable by using NDVs or the ALS instead of existing launch vehicles, the same payloads are assumed to be launched on both systems.

[20] M.E. Davies and W.R. Harris, *RAND's Role in the Evolution of Balloon and Satellite Observation Systems and Related U.S. Space Technology*, R-3692-RC (Santa Monica, CA: The RAND Corp., September 1988), p. 96.

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[21] Clarence J. Geiger, "The Strangled Infant: The Boeing X-20A Dyna-Soar," in Richard P. Hallion, *The Hypersonic Revolution*, vol. 2 (Wright Patterson Air Force Base, OH: ASD Special Staff Office, 1987).

Chapter 3

Space Shuttle Evolution

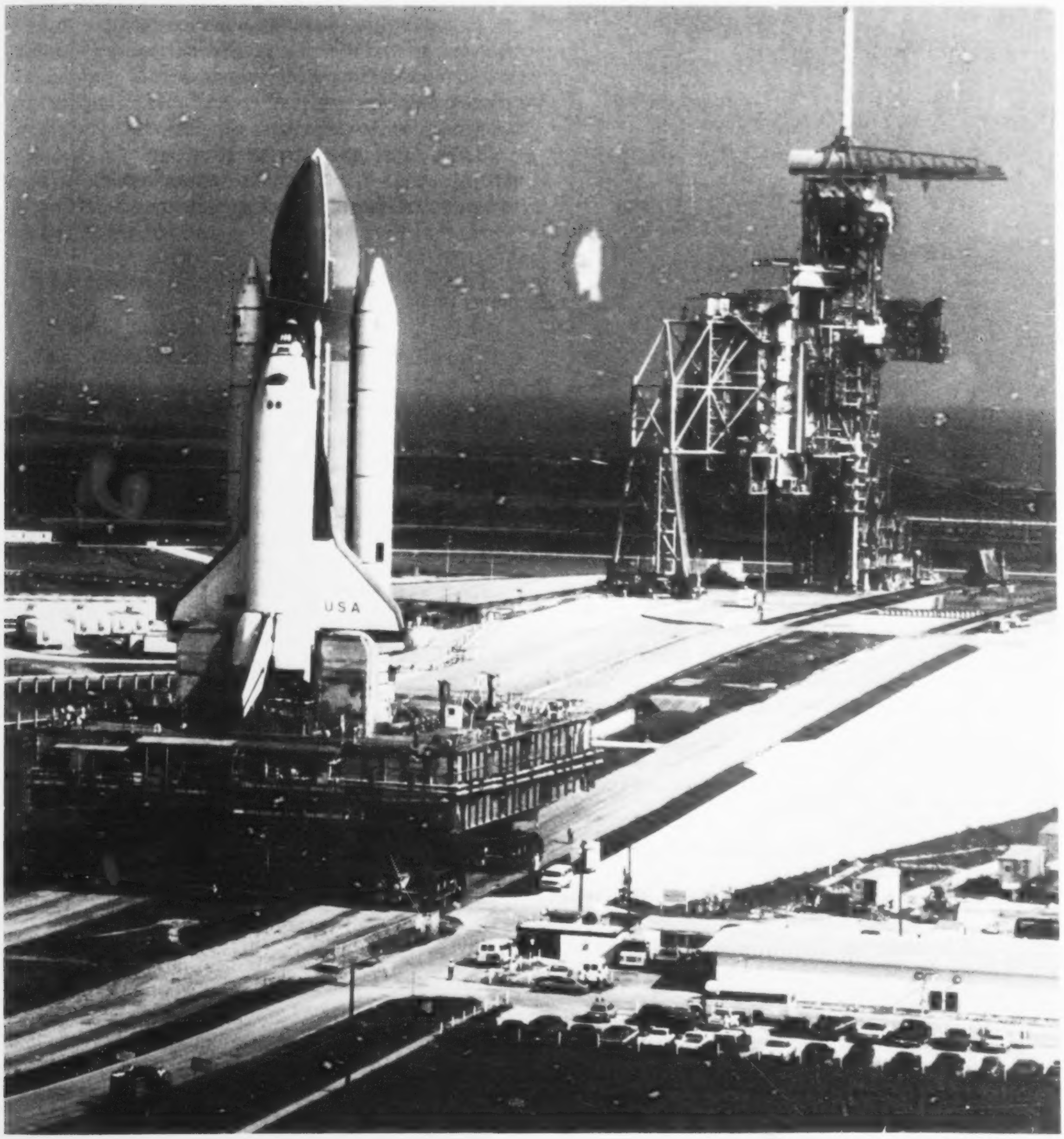

Photo credit: National Aeronautics and Space Administration

The Space Shuttle *Columbia* begins its roll up the ramp to pad 39A after completing the $3^1/_2$ mile journey from the Vehicle Assembly Building (September 1982)

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Chapter 3

Space Shuttle Evolution

INTRODUCTION

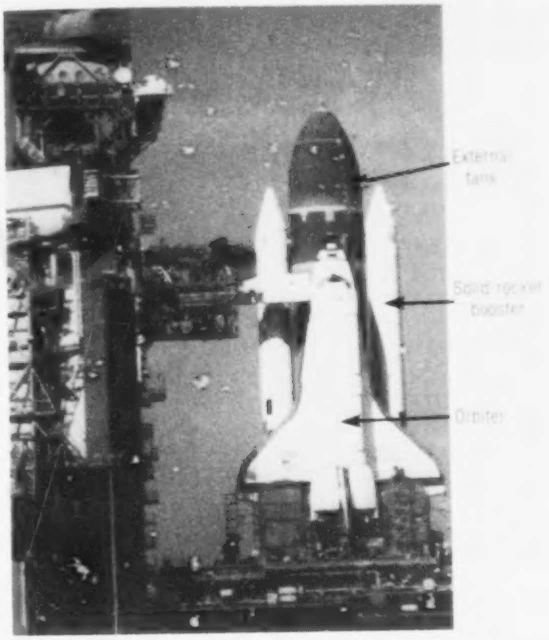
At some point early in the next century, Shuttle wearout, attrition, or a combination of advances in technology and the emergence of missions beyond the capacity of the Shuttle fleet will necessitate its replacement. New crew-carrying vehicles would incorporate advances in design, materials, and operations with the goal of attaining safe, reliable, cost-effective transport of humans to space. In the meantime, improvements to the current fleet may be cost-effective.

THE SPACE SHUTTLE SYSTEM TODAY

The Space Shuttle was the world's first partially reusable Earth-to-orbit launch vehicle (figure 3-1). Begun in 1972, the Space Shuttle was first launched in April 1981. It is capable of transporting both humans and heavy, large payloads into low-Earth orbit. Originally designed to carry payloads of 65,000 pounds to a reference orbit 110 nautical miles high, inclined by 28.5 degrees, Shuttles are now capable of carrying payloads of 52,000 pounds to the same orbit. As of May 1989, the National Aeronautics and Space Administration had successfully launched the Shuttle 28 times but experienced one tragic failure when one of the *Challenger's* Solid Rocket Boosters (SRBs) failed in January 1986.

At launch, the liquid-fueled Space Shuttle Main Engines (SSMEs) are ignited. If main engine operation appears normal, the SRBs are ignited 7 seconds later; otherwise the main engines can be shut down and the launch aborted. Once ignited, the SRBs cannot be shut down before they burn out,[1] nor can the Shuttle be safely held on the pad until the SRBs burn out should a malfunction occur. Two and one-half minutes into the flight, explosive bolts separate the orbiter from the SRBs, which parachute into the Atlantic Ocean and are recovered. After about 8 minutes of flight, the SSMEs shut down and the external tank separates from the orbiter, breaks up as it reenters the atmosphere, and falls into the Indian Ocean. In space, the Orbiter Maneuvering System (OMS) engines, fueled by hypergolic propellants,[2] propel the craft into the orbit desired for the mission.

Figure 3-1—Space Shuttle Elements



- *the orbiter*,[1] with the crew compartment and payload bay, which also contains the three Space Shuttle main engines (SSMEs). About the size of a DC-9, the orbiter weighs about 215,000 lbs. without its payload and has a 15 by 60 foot cylindrical payload bay.
- *the external tank*, which holds the liquid hydrogen fuel for the SSMEs, and the liquid oxygen used to burn it.
- *two segmented solid-fuel rocket boosters (SRBs)*. Each is made up of five Redesigned Solid Rocket Motor (RSRM) segments.

[1] There are now three orbiters—*Columbia*, *Discovery*, and *Atlantis*. A fourth orbiter, *Endeavor* will join the fleet in 1992.

SOURCE: National Aeronautics and Space Administration.

After the Shuttle crew completes its mission, the orbiter fires its OMS engines to leave orbit, reenters the atmosphere, glides to a runway, and lands. For safety reasons, especially after the loss of *Challenger*, Shuttle orbiters will normally land at Edwards Air Force Base, California. However, in an emergency, an orbiter could land at Cape Kennedy,

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[1] The SRBs can be destroyed in flight by the Range Safety Officer if, for example, the Shuttle veers out of control toward a populated area. Destroying the SRBs in flight would also destroy the Shuttle orbiter.

[2] A fuel and an oxidizer that ignite spontaneously when they come into contact. The OMS uses monomethyl hydrazine and nitrogen tetroxide.

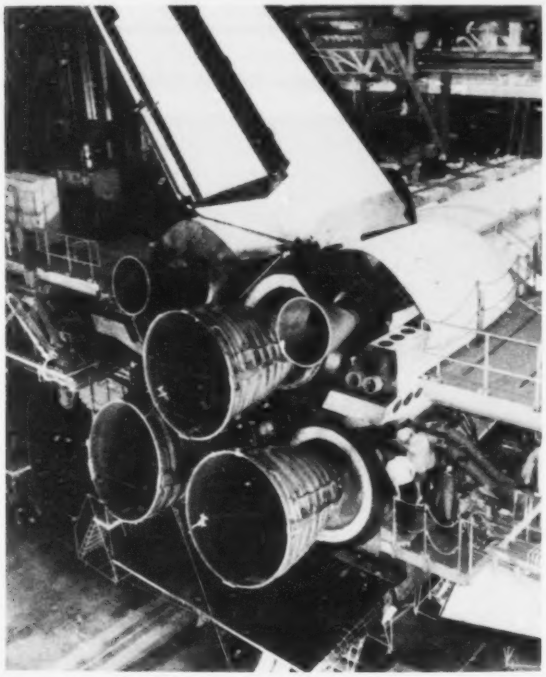

Photo credit: National Aeronautics and Space Administration

The Shuttle orbiter in the Orbiter Processing Facility, Kennedy Space Center. Visible are the orbiter's three Shuttle main engines and the two orbital maneuvering system engines to the right and left of the upper main engine.

Florida; White Sands Missile Range, New Mexico; Zarogosa, Spain; Casablanca, Morocco; Rota, Spain; or Guam. At the landing site, any remaining fuels are removed from the orbiter, and the orbiter is ferried atop a Boeing 747 aircraft to Kennedy Space Center, where it is refurbished for the next launch.

Many systems and facilities are required to process and launch a Shuttle and to communicate with and advise its crew during a flight. NASA refers to these systems and facilities, together with the fleet of Shuttle orbiters, as the National Space Transportation System (NSTS, or STS).

Figure 3-2 shows the main facilities at Kennedy Space Center (KSC) used for payload preparation and for Shuttle launch preparation, launch, and landing. The figure shows the Shuttle Landing Facility (runway), the Operations and Control Building, the Vehicle Assembly Building (VAB), the Orbiter Processing Facility, the Vertical Processing Facility, the Launch Control Center, and launch pads A and B of Launch Complex 39. Not shown are the SRB Disassembly Facility, the SRB Rotational Processing and Surge Facility, and the Mobile Launch Platform, on which the Shuttle is erected in the VAB. Facilities located elsewhere include the Michoud Assembly Facility near New Orleans, where external tanks are manufactured and shipped to KSC by barge, and the Lyndon B. Johnson Space Center (JSC) in Houston, Texas, where NASA plans the missions, trains crews, develops flight software, and controls missions via the Tracking and Data Relay Satellite System and communications and tracking stations located around the world. NASA also maintains the Shuttle Landing Facility at Edwards Air Force Base, California, where it uses a dry lake bed as a runway, and the emergency landing sites.

Launch operations include all the activities performed to maintain and launch Shuttles, including refurbishment of orbiters and solid rocket boosters after each flight. Figure 3-3 illustrates the operations performed at Kennedy Space Center.[3] The processing concept used at KSC is called "integrate—transfer—launch," or ITL. The vehicle is assembled on a Mobile Launch Platform in the Vehicle Assembly Building and carried to the launch pad. This minimizes orbiter time on the launch pad and permits higher launch rates than could be achieved with "integrate on pad" processing.

As soon as the Shuttle lifts off the launch pad, the mission is controlled from Johnson Space Center. Payloads (experiments) may be controlled from JSC, the Jet Propulsion Laboratory in Pasadena, California, or the Goddard Space Flight Center in Greenbelt, Maryland. But mission control is only one part of the operations requirements. Mission operations also include mission planning, training of the flight crew and ground crews, development of flight software, and the tasks performed by the flight

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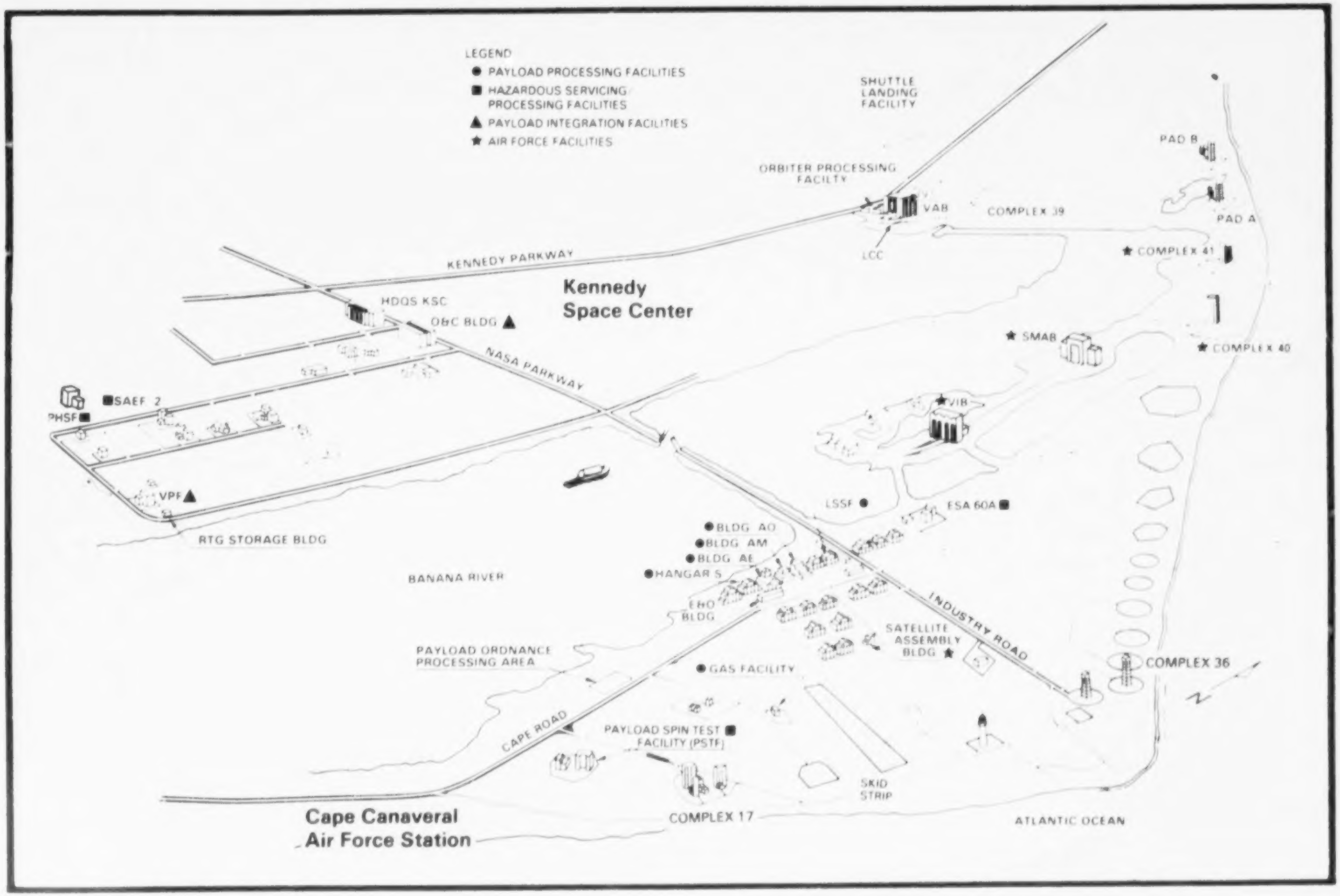
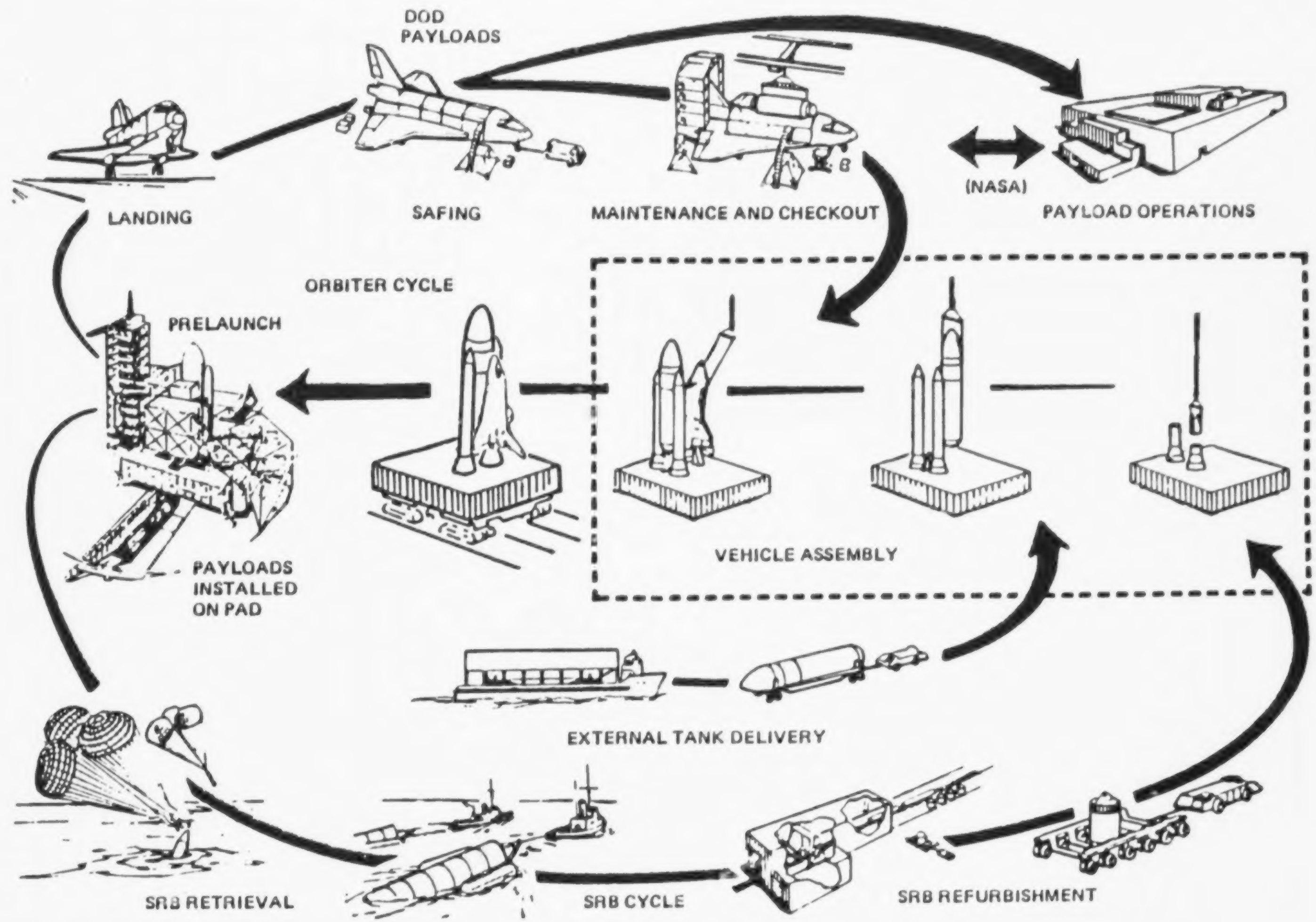
[3] For further details, see ch. 3 of U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

Figure 3-2—Kennedy Space Center Payload Facilities



SOURCE: National Aeronautics and Space Administration.

Figure 3-3—Kennedy Space Center Space Shuttle System Ground Flow



SOURCE: National Aeronautics and Space Administration.

crew in orbit. These activities may span 2 years or more for a specific flight.

SHORTCOMINGS OF THE SPACE SHUTTLE

U.S. dependence on the Space Shuttle for carrying crews to space raises questions concerning the longevity of the Shuttle fleet and the risk that orbiters might be unavailable when needed. These involve:

- the relative inflexibility of the Shuttle System, especially when scheduled to fly at rates close to the maximum sustainable flight rate;
- possible attrition of the Shuttle fleet as a result of unreliability; and
- eventual obsolescence.

NASA's Flight Schedule

NASA has estimated that 14 Shuttles can be launched per year from the Kennedy Space Center with existing facilities,[4] and NASA has scheduled 14 Shuttle flights per year in 1993. However, NASA has never launched more than 9 Shuttle flights per year, and many experts doubt that 14 launches per year can be sustained with a 4-orbiter fleet.[5]

The total number of workdays, or shifts, required to prepare an orbiter for launch is called the "turnaround time." Keeping it short is essential for reducing the cost per flight and increasing the sustainable flight rate; turnaround time limits the flight rate now. NASA's goal of 20 shifts has never been achieved. Actual turnaround time exceeded 200 three-shift workdays for the qualification (first) flights of each of the first three orbiters, but had been reduced to 55 three-shift days before the 25th flight, on which the *Challenger* was lost (figure 3-4). After that accident, NASA changed launch preparation procedures; NASA estimates the turnaround time for the first and second post-*Challenger* flights as 322 and 236 days respectively.[6] NASA expects that in 4 years, turnaround time will decrease to 75 days, which would allow 12 to 14 flights per year when a fourth orbiter is added to the fleet. NASA expects that a flight rate higher than 14 per year could not be attained merely by buying more orbiters; with four orbiters and a turnaround time of 75 three-shift days, the flight rate would be limited by current facilities. Additional orbiter processing facilities would be needed to achieve a flight rate higher than 14 per year.

In fact, NASA will have difficulty reaching a rate of 14 flights per year unless it is able to find ways of sharply reducing its current turnaround time. Its goal of 14 flights per year assumes a "success-oriented processing schedule" and no margin for contingencies. Yet NASA is not achieving the reductions of turnaround time it had anticipated. In addition, some NASA officials have expressed concern that the 90 days planned for structural inspections and orbiter modifications every three years may not be long enough to accomplish all potential necessary work.[7]

Inflexibility

If NASA does eventually prove capable of launching 14 Shuttle flights per year, scheduling launches at the maximum sustainable launch rate estimated by NASA leaves no margin to accommodate a sudden change in launch plans or to fly any missions that may be delayed by a future accident. If a Shuttle mission is changed, payloads and equipment for the original mission may have to be removed before equipment for the new mission can be installed.

If more margin were reserved in Shuttle launch schedules, an orbiter could be on hand to be outfitted quickly for an unplanned mission. This margin could be provided by scheduling fewer missions per year or by buying more orbiters—and more orbiter processing facilities, if they become a bottleneck.

However, even with more margin, it could take as long as a few months to prepare an orbiter for an unscheduled mission, because of the lead time required for mission planning, orbiter processing,

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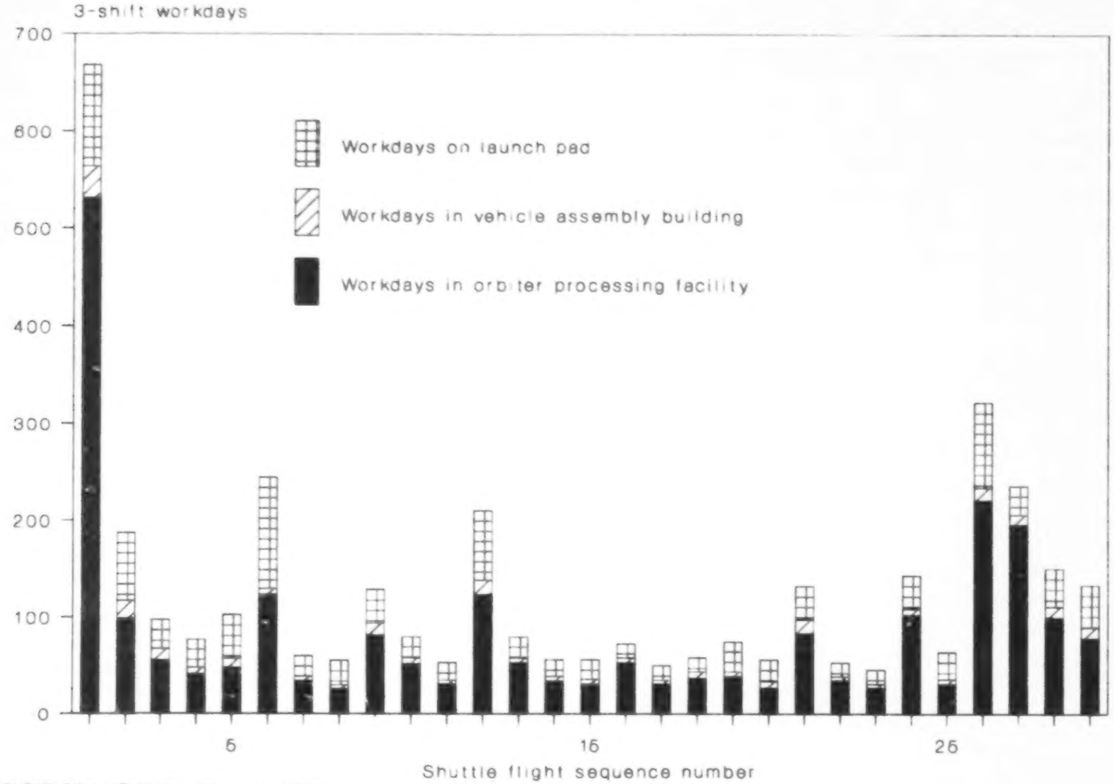
[4] Enclosure to letter from Darrell R. Branscome, NASA HQ, to Richard DalBello, OTA, Mar. 31, 1988.

[5] National Research Council, Committee on NASA Scientific and Technological Program Reviews, *Post*-Challenger *Assessment of Space Shuttle Flight Rates and Utilization* (Washington, DC: National Academy Press, October 1986), p. 15; Aerospace Safety Advisory Panel, *Annual Report* (Washington, DC: NASA Headquarters, Code Q-1, March 1989), p. iv.

[6] These estimates exclude the time spent improving the orbiters after the *Challenger* accident.

[7] NASA Kennedy Space Center briefing, Apr. 26, 1989.

Figure 3-4—Orbiter Ground Turnaround Experience



SOURCE: Office of Technology Assessment, 1989.

and crew training.[8] There would still be insufficient flexibility to, say, rescue a Space Station crewmember who has a critical illness or injury. For this, specially designed escape or rescue vehicles (discussed in ch. 6) might be needed.

Eventually, flexibility to schedule unplanned Shuttle missons may decrease because of Shuttle fleet attrition. Scheduling fewer missions per year would compensate for this erosion of flexibility by slowing the attrition of orbiters—but also at the cost of foregoing opportunities for transporting people to space. **If the Nation wishes to improve the safety of its crew-carrying space flight program while increasing its flexibility, NASA and the Defense Department will have to allow more margin in Shuttle launch vehicle schedules.**

Risk of Attrition

NASA intended each orbiter to last 100 flights with a probability of at least 97 percent.[9] If average Shuttle "life" were limited primarily by attrition, this design specification would require a 99.97 percent probability of recovering the orbiter in refurbishable condition after each launch;[10] if fatigue or wearout were significant, the probability would have to be even higher. Orbiter recovery reliability was probably lower during the first 25 flights; if it had been 99.97 percent, the odds against losing an orbiter in the first 25 flights would have been greater than 130 to 1. The reliability that would have made the observed success rate most likely is 96 percent; the actual reliability is uncertain.[11]

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[8] Normally, Shuttle crews, payloads, and specific orbiter are chosen up to 2 years prior to a flight, in order to provide enough time for payload integration and crew training.

[9] Space Shuttle Phase C/D work statement design specifications.

[10] A failure to recover the orbiter in refurbishable condition after a launch could be caused by a failure of the orbiter, a failure of some other system, human error, or unexpected conditions (e.g., lightning at launch).

NASA officials believe that Shuttle reliability was improved after the loss of *Challenger* because some failure modes were eliminated.[12] However, NASA has not estimated **how much** reliability has been improved, because NASA does not routinely estimate Shuttle reliability quantitatively,[13] although it has done so for planned missions that will employ nuclear power systems.[14]

Estimates based partly on judgment vary widely. For example, the late Richard Feynman, a member of the Presidential Commission appointed to investigate the *Challenger* accident, called the Shuttle "... relatively unsafe ..., with a chance of failure on the order of a percent," adding "It is difficult to be more accurate."[15] A NASA contractor estimated that post-*Challenger* Shuttle reliability would be between 97 and 98.6 percent, with most failures caused by propulsion failures during ascent.[16] And while one NASA division estimated that on the Galileo mission the orbiter will have a 99.361 percent probability of remaining intact until deployment of the Jupiter-bound Galileo space probe begins,[17] another NASA division estimated the probability would likely lie between 1 in 36 (97.2 percent) and 1 in 168 (99.4 percent).[18]

The uncertainty in Shuttle reliability on past missions may be expressed in terms of statistical confidence bounds. In essence, for each of several possible values of reliability (called a lower confidence bound), one calculates a confidence level on the probability that more failures would have occurred than the number that did occur.[19] If the confidence level for a lower confidence bound exceeds 50 percent, it is improbable that the observed number of successes would have occurred unless the reliability exceeded the lower confidence bound. This approach is objective[20] and takes into account all factors, including human factors, that may not affect the reliabilities of engines or other components during ground tests. On occasion, NASA has used confidence bounds.[21]

The method of confidence bounds possesses the shortcoming that, even if reliability is high, many launches are required to provide high statistical confidence that it is. **The 29 Shuttle launches to date provide only 50 percent statistical confidence that Shuttle reliability has been at least 94.3 percent. If the reliability is now actually 94.3**

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[11] The probability of safely recovering the crew may differ from orbiter recovery reliability, because the crew might survive situations in which the orbiter would be lost (e.g., main engine shutdown followed by crew bail-out and ditching of the orbiter at sea).

[12] However, potential new failure modes were introduced. For example, radial bolts have been added to the nozzle-to-case joint in the SRBs, creating new possibilities for blow-by or crack propagation. See Richard DeMeis, "Shuttle SRB: NASA's Comeback Bid," *Aerospace America*, April 1987, p. 32 ff.

[13] James H. Fletcher, "Risk Management Policy for Manned Flight Programs," NASA Management Instruction NMI 8070.4, effective Feb. 3, 1988; Trudy E. Bell and Karl Esch, "The Space Shuttle: A Case of Subjective Engineering," *IEEE Spectrum*, June 1989, pp. 42-46.

[14] General Electric Astro Space Division, *Final Safety Analysis Report II for the Galileo Mission*, doc. 87SDS4213 (Valley Forge, PA: General Electric Astro Space Division, August 1988).

[15] *Report of the Presidential Commission on the Space Shuttle* Challenger *Accident*, App. F. (Washington, DC: U.S. Government Printing Office, 1986); R.P. Feynman, *What Do You Care What Other People Think?* (New York, NY: W.W. Norton & Co., 1988), p. 236.

[16] L-Systems, Inc., *Shuttle/Shuttle-C Operations, Risks, and Cost Analyses*, LSYS-88-008 (El Segundo, CA: 1988).

[17] General Electric Astro Space Division, op. cit., NASA supplied no rationale for its estimates of failure probabilities from which General Electric calculated this probability, and NASA specifications had the effect of masking the overall uncertainty.

[18] NASA, Code QS, cited in chapter 2. The probability of orbiter recovery after the Galileo mission would be comparable to the mission success probability, because the most likely causes of a mission failure would probably destroy the orbiter.

[19] Y. Fujino, "Approximate Binomial Confidence Limits," *Biometrika*, vol. 67, No. 3, 1980, pp. 677-681; see also C.R. Blyth and H.A. Still, "Binomial Confidence Intervals," *Journal of the American Statistical Association*, vol. 78, No. 381, March 1983, pp. 108-116.

[20] Subjective methods, if logically consistent, can also be valuable. See M.G. Morgan and M. Henrion, *Uncertainty* (Clarendon, England: Cambridge University Press, in press).

[21] See, e.g., Jerry J. Fitts, NASA Transportation Services Office, "Payload Backlog, Flight Rate Capability, Reliability and Downtime—Briefing for Dale Meyers," Nov. 5, 1987, rev. Dec. 9, 1987.

percent, there would be a better than even chance of losing at least one orbiter on the next 12 flights (figure 3-5).[22]

If reliability is, or becomes, higher, additional flights will eventually provide greater statistical confidence that is. But if it is judged more important to have four orbiters in the mid-1990s than to have high launch rates now, conservative planning would allow for the possibility that reliability might be lower than 94.3 percent by ordering one or more additional orbiters as soon as possible and limiting Shuttle launch rates until the first one becomes operational. Even if reliability is 98 percent, launching Shuttles at the rates now planned would make it unlikely that Space Station assembly could begin before another orbiter is lost (see box 3-A and figure 3-6).

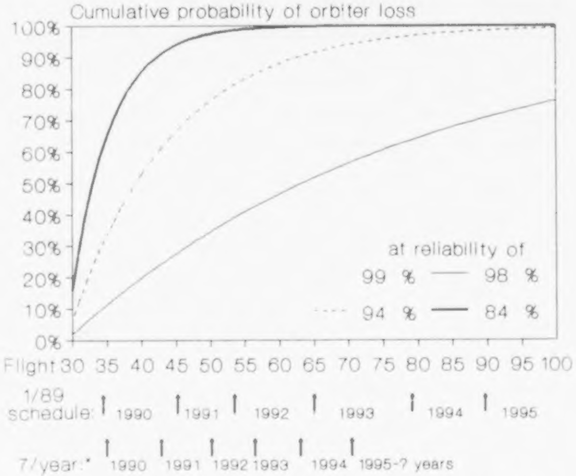
Obsolescence

After sufficiently many flights, an orbiter's airframe could be so weakened by fatigue as to be unsafe. Replaceable parts may also wear out; when they do, replacement parts may no longer be available from manufacturers. The manufacturers that built them originally may have stopped making such parts, the tooling used to build them may have been destroyed, and the skilled workers who made them may have left or retired. If sufficient spare parts have not been stockpiled, replacement parts may have to be custom-made, and this may require new tooling, training of workers, extra expense, and delay.

Existing Shuttle orbiters will be at least 15 years old in the mid-1990s, when Space Station operations are scheduled to begin. By that time, the designs of most Shuttle systems will be 25 years old. On occasion, it will be economical to replace some systems before they wear out, because redesigned systems would be so much less expensive to operate that the cost of upgrading would be justified. Eventually, it will be economical to replace the entire orbiter fleet with a fleet of newly designed vehicles that can be operated at lower life-cycle cost.

NASA is now estimating the costs of operating improved Shuttle orbiters and newly designed vehicles that would be used in an Advanced Manned Launch System. NASA, the Air Force, and their contractors are also estimating the costs of operating spaceplanes that could be built using technology to be demonstrated by the experimental X-30 spaceplane. When these estimates are completed, comparisons of cost-effectiveness can be made to forecast economically optimal dates for phasing out orbiters of existing design and introducing improved Shuttle orbiters, a Personnel Launch System, an Advanced Manned Launch System, and/or operational spaceplanes incorporating X-30 technology.

Figure 3-5—Effect of Flight Rate on Shuttle Orbiter Attrition



*Compare expected attrition at a launch rate of seven per yr

These graphs show the cumulative probability that at least one orbiter will not be recovered after a flight, starting with flight 30, for four possible values of orbiter recovery reliability: 84%, 94.3%, 98%, and 99%. The actual value of orbiter recovery reliability is uncertain. 84% is the lower confidence bound on post-*Challenger* reliability at a confidence level of 50%. 94.3% is the lower confidence bound on reliability at a confidence level of 50%, based on all flights to date. 98% is the nominal post-*Challenger* reliability estimated by L Systems, Inc., and 99% is consistent with a NASA estimate of Shuttle reliability on the *Galileo* mission (see text).

Reducing the flight rate would slow the growth of the cumulative probability of orbiter loss. For example, reducing the flight rate from that scheduled by NASA in June 1989 to a rate of five flights per year beginning 1990 would reduce the probability of orbiter loss by 1995 from about 70 percent to about 44 percent, if the orbiter recovery reliability were 98 percent.

SOURCE: Office of Technology Assessment, 1989.

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[22] The four post-*Challenger* launches to date, all successful, provide only 50 percent confidence that post-*Challenger* reliability has been at least 84 percent. If the reliability is 84 percent, there would be a better than even chance of losing an orbiter on the next four flights.

NEAR-TERM OPTIONS

In the near-term the Nation could choose one or more of the following options:

- purchase additional orbiters—either copies of the orbiter (OV-105) now being built, or improved orbiters;
- improve existing orbiters;
- improve other Space Shuttle elements or facilities; or
- develop Space Station escape capsules or a Personnel Launch System to complement the Shuttle fleet.

The following sections discuss the first three options. The last one is discussed in chapter 6.

Option 1: Buy Additional Orbiters

Buying more orbiters would increase the resiliency of the Space Shuttle system, i.e., its ability to recover rapidly from loss of an orbiter or any other event that delays launches. As noted in earlier sections, the Shuttle orbiter fleet is likely to continue to suffer occasional attrition.[23] Loss or prolonged unavailability of one orbiter would throw NASA's plans for Space Station assembly and servicing into disarray and could lead to loss of life.[24]

The Shuttle prime contractor, Rockwell International, argues that the Shuttle system could still be flying in 2020. Although this is theoretically possible, it may not be desirable, primarily because of obsolescence. The Shuttle will remain the crew-carrying workhorse well into the next century, but other more cost-effective options will also be pursued.

The company also believes that even in the absence of attrition, the percentage of time the orbiters are likely to spend being inspected, modified, or refurbished requires NASA to maintain five orbiters in order to assure use of four.[25] Rockwell officials similarly argue that having a slightly larger fleet, or "fleet margin" would allow for unexpected contingencies and unscheduled downtime.

Box 3-A—Shuttle Attrition and Space Station Assembly

The Shuttle fleet now consists of three orbiters; a fourth is to become operational in 1992. All 4 orbiters will be needed to fly the missions now scheduled for 1992-95 and planned for 1995-97, when NASA plans (but has not yet scheduled) 21 Space Station assembly flights. Figure 3-6 shows the probabilities that all 4, or at least 3, orbiters will survive flights 30 to 200, if post-*Challenger* Shuttle reliability is 98 percent.[1] If NASA adheres to its current schedule through 1994 and flies 14 flights per year thereafter, Space Station assembly would begin by about flight 92 and be completed by about flight 134. There is little statistical confidence that orbiter recovery reliability is at least 98 percent—only 7.8 percent confidence based on the four post-*Challenger* flights, or 11.4 percent confidence based on all flights to date. (See text for a discussion of statistical confidence.)

[1] L-Systems, Inc., *Shuttle/Shuttle-C Operations, Risks, and Cost Analyses*, LSYS-88-008 (El Segundo, CA: L-Systems, Inc., 1988).

Rockwell estimates that, starting from scratch, an orbiter could be built in about 6 years. If some structural spares are available, the time could be reduced by about a year. Thus, if a new orbiter (OV-106) were needed by, say, 1996, the decision to build spares would have to be made in 1990. A decision to purchase OV-106 could be delayed until fiscal year 1991. Major structural components for the Shuttle can take 4 to 5 years to produce. Space Shuttle Main Engines (SSMEs) now require 4 years. Orbiter OV-105,[26] ordered to replace the *Challenger*, was begun in 1987 and is scheduled for completion late in 1991.[27] It will be ready in such a relatively short time because major components

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[23] Post-*Challenger* Assessment of Space Shuttle Flight Rates and Utilization, National Research Council (Washington DC, National Academy Press, October 1986); Report of the Committee on the Space Station of the National Research Council (Washington DC: National Academy Press, September 1987). See also L-Systems, Inc., "Shuttle/Shuttle-C Operations, Risks and Cost Analyses," El Segundo, CA, LSYS-88-008, July 21, 1988, which analyses the probability of supporting Shuttle commitments under differing assumptions of fleet size, flight rates, and reliability.

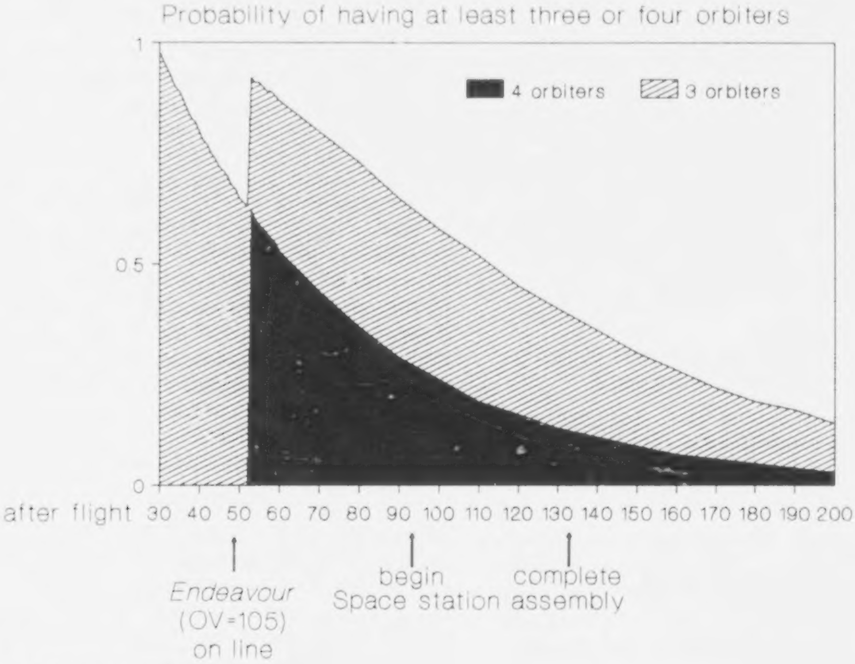
[24] Loss of life could occur if resupply to the Station is late.

[25] Rockwell presentation to OTA, Nov. 15, 1988, p. 20. The L-Systems report also makes a compelling case for replacement and spare orbiters.

[26] In May 1989, President Bush named this new Space Shuttle orbiter *Endeavour*, after the first ship commanded by James Cook, the British explorer who was the first European to discover Hawaii.

[27] First flight is expected early in 1992.

Figure 3-6—Shuttle Attrition if Orbiter Recovery Reliability is 98 Percent



SOURCE: Office of Technology Assessment, 1989.

already existed as spares. If too long a period passes between major component buys, some of the expertise and physical plant required for manufacture could be lost, leading to even longer lead times.

If Congress decided to proceed with building a new orbiter, it has three basic options. Congress could direct NASA to construct an orbiter:

- that is a copy of OV-105;
- designed for increased safety, performance (e.g., endurance), and economy; or
- with reduced weight to increase payload capability or with other improvements (e.g., an improved escape system).

Build a Copy of OV-105 (*Endeavour*)

OV-105 is itself a greatly upgraded vehicle compared with its predecessors and includes:

- addition of an escape hatch, with an extended pole to allow crew members to slide down and parachute to safety;
- external changes including improved heat absorbing tiles, changes to the landing gear, strengthening of the wing structure and engine pod; and
- more than 200 internal changes including electrical rewiring and changes in the braking and steering systems. Because of these improvements, building OV-106 identical to OV-105 would still represent considerable modernization of the fleet.

Improve Safety, Performance, and Economy

For the second option, a large number of potential new upgrades have been identified by the orbiter prime contractor, Rockwell, and are shown in table 3-1. These have been categorized into the three basic areas of safety and reliability, cost reduction, and performance, although each change has benefits in several categories. Orbiter upgrades are being continually defined and evaluated so that the list itself is dynamic. NASA/JSC is studying the costs and benefits of possible improvements with a view to identifying the most important improvements.

The orbiter cockpit could be made into a crew escape module to allow the crew to escape in some situations in which the existing escape pole system[28] is unusable. However, a crew escape module would be heavier and more costly;[29] developing it would be a very difficult project and its utility is the subject of considerable debate.

Space Shuttle main engine improvements that would increase engine life and reliability are already under way. They include improved welds, improved manufacturing techniques, improved nondestructive testing, improved heat exchangers, improved controllers, improved power head, engine health monitoring,[30] alternate turbopump development (see box 3-B), and a technology test bed.[31]

The on-board computers of future launch vehicles, or existing orbiters, could consist of identical computer modules "mass-produced" for economy (possibly even commercial modules) and connected by optical fibers for reduced susceptibility to electromagnetic interference.[32] Computers with a high degree of fault-tolerance would also allow the launch of a vehicle with a known fault rather than holding the launch to replace a failed module and retest the system.

The length of time an orbiter can remain in orbit could be extended.[33] NASA states that "extended duration orbiters" will allow NASA to fly missions lasting 16 to 28 days (current orbiters are limited to 7 days). This would be useful for SpaceLab and for tending the Space Station in the crew-tended phase, or servicing commercially developed space facilities.[34] It would also provide experience in technology areas beneficial for future space operations.

A Shuttle orbiter could be given the capability to fly an entire mission automatically, as the Soviet shuttle *Buran* did on its first flight. Without a crew, an automatic orbiter could carry extra payload. With a crew, such an automatic orbiter could land even if Shuttle pilots were incapacitated (e.g., by a depressurization accident).

Table 3-1—Selected Possible Upgrades for New Orbiters

***Safety & reliability*:**
- Assured crew return
- Simplified hydraulics
- Increased strength skins
- Improved attitude control
- Suppressed helium overpressure

***Cost reductions*:**
- Simplified cooling
- Modernized crew displays
- Improved tile durability
- Modernized telemetry

***Performance*:**
- Extended duration orbiter
- Weight reduction
- Local structure strengthening
- Global Positioning Satellite (GPS) receiver-computer for navigation

SOURCE: Rockwell International Corp.

Reduce Weight

The third option would involve significant weight reduction of the airframe. Orbiter airframe weight reductions of 8,000 to 10,000 pounds for both retrofittable and nonretrofittable structures could be achieved through the use of composite materials, alloys, intermetallics, and high-temperature metallics. This would allow payload capability to be increased by the amount orbiter weight is reduced (i.e., up to 10,000 pounds) or allow an improved escape system or other systems to be installed without sacrificing payload capability. About 10,000 pounds of weight reduction would provide the equivalent of one extra launch of 60,000 pounds of payload in one and one-half year of OV-106 flights (approximately six launches). The choice of specific airframe structural modifications would depend on cost-benefit analyses.

---

[28] The escape pole system is only good under stable flight conditions at relatively low speeds.

[29] George Marsh, "Eject, Eject, Eject," *Space*, January-February 1988, pp. 4-8.

[30] In other words, being able to diagnose engine operation when it is firing. This leads to improved performance and potentially can signal if engine shutdown is necessary to avoid catastrophic failure.

[31] J.W. Smelser, MSFC, presentation to OTA, Sept. 21, 1988.

[32] *Reducing Launch Operations Costs*, op. cit., footnote 3, p. 63.

[33] Dwayne Weary, JSC, presentation to OTA, Sept. 22, 1988.

[34] It would generally be useful for a whole class of experiments. See OTA's Space Station study: *Civilian Space Stations and the U.S. Future in Space* (Washington, DC: U.S. Congress, Office of Technology Assessment, OTA-STI-241, November 1984).

Box 3-B—Alternate Turbopump Development

Improving the lifetime of the SSME is a good example of a significant incremental improvement. NASA has a $228 million contract with Pratt and Whitney to build an alternate fuel and oxidizer turbopump that will be more durable and reliable than the existing ones.[1] Pratt and Whitney will attempt to bring the engines closer to their intended 55 missions (approximately 7.5 operating hours), between costly teardowns.[2] NASA's design goals call for 30 missions before removal for minor seal and bearing replacements, and another 30 missions before major overhaul. This would cut SSME refurbishment time and operational costs. These turbopumps are designed to be completely interchangeable with the existing Rocketdyne pumps, have more benign failure modes for greater safety, and will have only 4 welds compared to the present 297. The table below lists some of the ATD enhancements and advantages to date. The new turbopump borrows heavily from Pratt and Whitney's experience building the T800 helicopter engine; additional development is required for withstanding the harsh operating environment of ultra-high pressures, cryogenic temperatures, and possible hydrogen embrittlement.

Benefits of Alternate Turbopump Development

Principle:

- Design for producibility utilizes precision castings and new processes and materials, thereby minimizing number of welds, parts, and coatings.

Results to Date:

- Number of welds reduced from 297 to 4.
- Rotor stack details reduced from 80 to 39
- No coatings in hot turbopump sections

Benefits:

- Improved turbomachinery quality
- Improved part-to-part repeatability
- Improved durability
- Reduced machining requirements
- Reduced manufacturing lead time by 20 months
- Reduced turbomachinery cost ($3 million per pump set)

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[1] Frank Colucci, "Space Power From Florida," *Space*, Nov-Dec 1988, pp. 10-12; Edward H. Kolcum, "Pratt and Whitney Engine Turbopumps Could Fly on Space Shuttle in 1992," *Aviation Week and Space Technology*, Feb. 27, 1989.

[2] Up to the present, the engines have had complete turbine blade inspections after every mission.

Some of these upgrades could not be retrofitted into existing vehicles because they would require extensive and expensive structural changes.

Option 2: Improve Existing Orbiters[35]

Redesign and improvement for all Shuttle systems is a continuing process.[36] However, NASA, through the Johnson Space Center, has begun to examine how best to improve the existing Space Shuttle system by making incremental changes. The first effort studies major evolutionary modifications that could be applied to the existing Shuttle fleet. This evolutionary path is becoming increasingly attractive to NASA because it would allow a phased implementation of improvements, is relatively low-risk, and would not require "new program" funding—funding that is often difficult to obtain, particularly when the overall U.S. budget is so constrained. Major upgrades to the existing fleet could be accomplished during the regularly scheduled structural inspection program (every 3 years), bringing the entire fleet up to improved levels. However, NASA would have to reduce its expectations for the Shuttle schedule in order to have enough time to make these modifications. As noted above, meeting the manifested launch rate of 14 flights per year presents a major challenge to NASA, even in the absence of major modifications to the Shuttle system.

Improved Space Shuttle main engines and computers, discussed above, could be installed on existing orbiters.

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[35] See also Gene Austin, MSFC, "Shuttle Evolution/Follow-On," Sept. 21, 1988, and C. Teixeira, JSC, Sept. 22, 1988.

[36] Because of the modular nature of the Space Shuttle system, some changes can take place outside of orbiter changes.

Reduce Airframe Weight

The airframe weight of existing orbiters (or OV-105) could be reduced, but not by as much as the airframe weight of a new orbiter could be reduced. This would allow payload capability to be increased by the amount orbiter weight is reduced, or allow an improved escape system or other systems to be installed without sacrificing payload capability.

Crew Escape Module

The cockpit of an existing orbiter could be made into a crew escape module to allow the crew to escape in some situations in which the existing escape pole system would be unusable. A crew escape module would be heavier and more costly; installation on an existing orbiter would be more costly, in terms of payload capacity sacrificed, than would installation on a new orbiter, because the airframe weight of a new orbiter could be reduced by a greater amount.

Automatic Orbiter Kit

An existing Shuttle orbiter could be given a capability to fly an entire mission automatically. This would require installation of a kit consisting of additional automatic control equipment (in the orbiter galley) and cables. Rockwell International estimates that it would take 2 years and cost $200 million to automate a first orbiter and $30 million to $40 million each for successive orbiters. Rockwell designers estimate the most difficult problem will be steering and braking after landing.

Extending Duration in Orbit

An existing Shuttle orbiter could also be made an Extended Duration Orbiter by installing fuel cell pallets in the payload bay, and additional life support supplies.

Option 3: Improve Other Space Shuttle Elements or Facilities

Space Shuttle elements other than the orbiter could also be improved, or replaced by newly designed elements.

Continue Development of Advanced Solid Rocket Motors [37]

The *Challenger* accident was caused by a failure in a solid rocket motor.[38] After the accident, NASA redesigned the solid rocket motors (SRMs) to improve reliability; these redesigned solid rocket motors (RSRMs) have been used on all subsequent Shuttle flights. Seeking even higher reliability, as well as higher performance, NASA has also initiated development of Advanced Solid Rocket Motors (ASRMs). They are to weigh less than RSRMs but produce more thrust, allowing Shuttles to carry up to 12,000 pounds of additional payload to orbit. Figure 3-7 illustrates the expected improvement in ASRM payload capability with respect to the present RSRM. Some NASA officials have expressed concern over whether the full additional lift capability of 12,000 pounds will be achieved. Their concerns are the result of past experience with launch systems.[39] Program officials at Marshall are confident that the 12,000 pound lift increase for the ASRMs can be achieved, as they have incorporated a lift margin to allow for weight growth of the solids. Many also feel that even if the lift increase goal is not completely met, that the other advantages of the ASRMs such as increased reliability, reproducibility, and a second supplier for of solids will make them worthwhile. NASA expects that the ASRM program will promote a competitive solid rocket motor industry and encourage commercial initiatives.[40] NASA has estimated the cost of the ASRM program at $1.3 billion, of which $1 billion would be for ASRM design, development, testing, and evaluation, and the rest for facility construction.

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[37] See also, U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, pp. 27-28.

[38] *Challenger* was launched in weather much colder than the solid rocket motors were certified to tolerate.

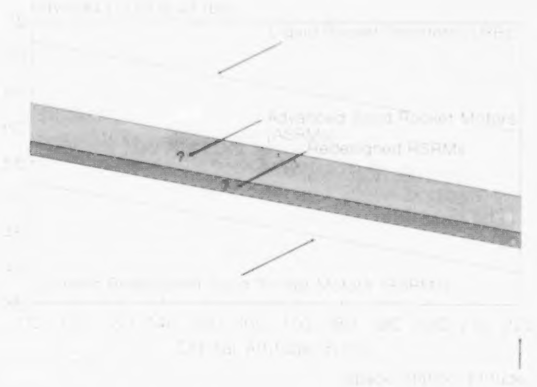
[39] For example, as noted earlier, the original Shuttle performance goal was 65,000 pounds to 110 nmi, 28.5 degrees. But the existing Shuttle only achieves 52,000 pounds to this orbit. This decrease in lift capability arose from weight growth of the Shuttle itself and lower than expected performance from the propulsion systems.

[40] NASA, "Space Shuttle Advanced Solid Rocket Motor—Acquisition Plan," Mar. 31, 1988, p. 3.

[41] Aerospace Safety Advisory Panel, op. cit., p. 3, and press briefing, Mar. 28, 1989.

[42] Ibid., loc. cit. See also, Eliot Marshall, "Shuttle Rocket Plan Under Fire," *Science*, vol. 244, pp. 135-136.

Figure 3-7—Expected Shuttle Payload Capability With Proposed Boosters



SOURCE: Office of Technology Assessment, 1989.

In March 1989, NASA's Aerospace Safety Advisory Panel (ASAP) announced its finding that "on the basis of safety and reliability alone it is questionable whether the ASRM would be superior to the RSRM . . . until the ASRM has a similar background of testing and flight experience. This may take as long as 10 years. . ."[41] The ASAP recommended "that NASA review its decision to procure the Advanced Solid Rocket Motor and postpone any action until other alternatives . . . have been thoroughly evaluated."[42] NASA disagreed with the ASAP findings and, in late April 1989, it awarded two contracts to a partnership formed between Aerojet and Lockheed.[43] One contract is for design and development of the ASRM; the other is for the design, construction, and operation of an automated solid rocket motor production facility. NASA has designated Yellow Creek, Mississippi as its preferred GOCO (government-owned/contractor-operated) ASRM production site and the Stennis Space Center in Mississippi as the motor test location. ASRMs could be ready for a first launch in 1994 or 1995.

Improve Redesigned Solid Rocket Motors

The *Challenger* disaster was attributed to a failure of one of the Solid Rocket Motors.[44] This prompted a program that redesigned the motor's joints and made other improvements, some of which were in process even before the Shuttle explosion. Many of the improvements in the RSRMs relate to ablative and insulation materials processing and nondestructive testing techniques. As of May 1989, the RSRMs have now performed successfully on four Shuttle flights.[45]

The thrust of the RSRMs could be improved by 6,000 to 8,000 pounds by substituting a more energetic solid propellant and by performing other requisite changes to the motors.[46] The additional thrust would increase the Shuttle's payload capacity by the same amount but might decrease unreliability. NASA has not estimated the cost of such improvements, but qualification testing alone would require about 10 rocket firings at $10 million to $12 million per test. These improved thrust RSRMs would be ready for flight before 1995, which is when ASRMs are scheduled to replace the existing RSRMs. More extensive changes could give a payload increase of 13,000 pounds.[47]

Develop Liquid Rocket Boosters (LRBs)[48]

At the same time that NASA was planning its ASRM work, propulsion experts inside NASA and in the aerospace community began to reconsider the practicality of replacing the current SRMs with

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[41] Aerospace Safety Advisory Panel, op. cit., p. 3, and press briefing, Mar. 28, 1989.

[42] Ibid., loc. cit. See also, Eliot Marshall, "Shuttle Rocket Plan Under Fire," *Science*, vol. 244, pp. 135-136.

[43] Immediately after the ASAP annual review on Mar. 28, 1989, NASA Administrator James Fletcher announced to the press that NASA would award the ASRM Phase C/D contracts as planned, despite the ASAP concerns. One reason was that the funds had already been authorized.

[44] *Report of the Presidential Commission on the Space Shuttle* Challenger *Accident*, op. cit.

[45] *Discovery:* Sept. 29, 1988; *Atlantis:* Dec. 2, 1988; *Discovery:* Mar. 13, 1989; *Atlantis:* May 4, 1989.

[46] See response by Morton Thiokol, Inc. to NASA Marshall Space Flight Center request to provide candidate NSTS payload performance improvements directly related to RSRM changes. Memo L060-FY89-170, Apr. 3, 1989.

[47] Ibid.

[48] *Launch Options for the Future: A Buyer's Guide*, op. cit., footnote 38, pp. 28-29.

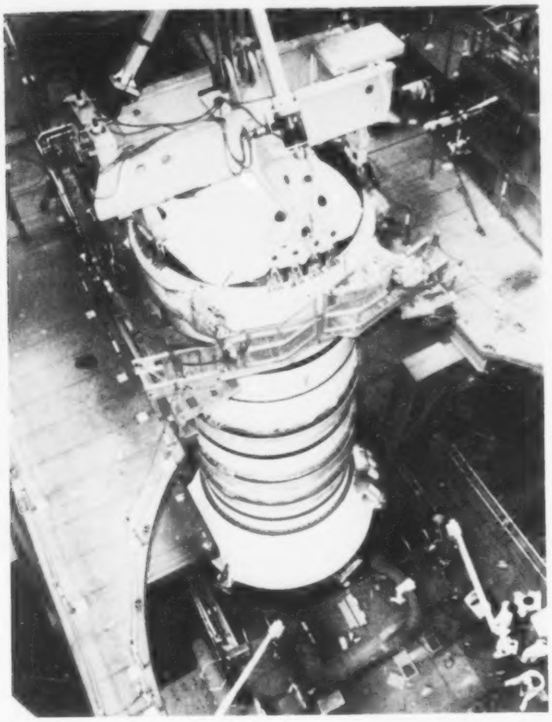
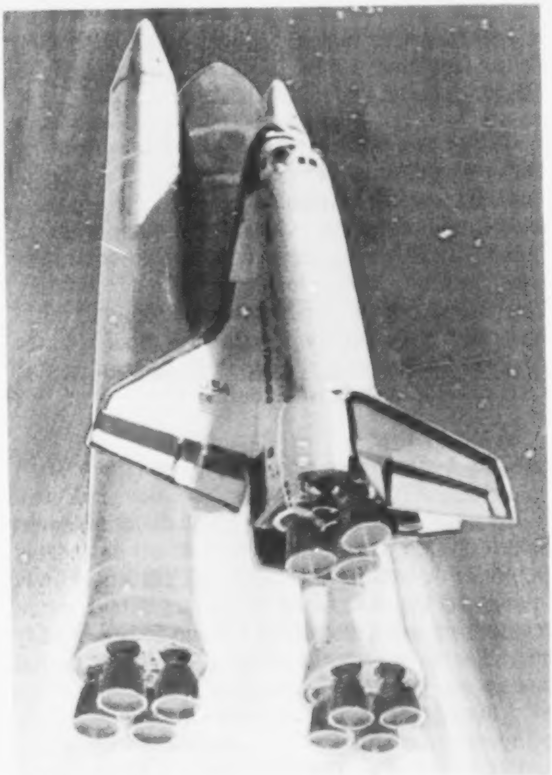


Photo credit: National Aeronautics and Space Administration

One of the Shuttle's redesigned solid rocket motors being attached to the mobile launch platform, Kennedy Space Center.

Figure 3-8—Space Shuttle With Proposed Liquid-Fuel Rocket Boosters (LRBs) (artist's conception)



SOURCE: General Dynamics.

Liquid Rocket Boosters.[49] Initial studies indicate that LRBs could replace or complement the RSRMs or the ASRMs on the Shuttle, but would require some redesign of Shuttle and launch pad systems.[50]

NASA estimates that development and testing for the liquid booster alone would cost $3 billion spread over 8 years.[51] Pad modifications would cost $500 million. A conceptual drawing of the Shuttle atop LRB rockets (two pods of four liquid engines each) is shown in figure 3-8.

Private sector interest in LRBs has been substantial. General Dynamics (one of the LRB study contractors as was Martin Marietta) has proposed a "National Liquid Rocket Booster Program." This would develop an LRB (liquid oxygen/liquid hydrogen fueled) in conjunction with sped up ALS propulsion efforts since the size, thrust, and weight requirements for both engines are virtually the same. Potentially large cost savings could accrue compared to developing each separately.[52] The Rocketdyne Division of Rockwell International has also worked on modifying some of their existing engine hardware into an "RSX" configuration (liquid oxygen/kerosene fueled) for use on an LRB.[53] Both firms feel that LRBs could be developed for substantially less than $3 billion.

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[49] LRBs were originally studied at the inception of the Shuttle program but were rejected in favor of solids when it was estimated that LRB development would cost $500 million more and would take at least 1 year longer than solids. (U.S. Congress, House Committee on Science, Space and Technology, Subcommittee on Space Science and Applications, Space Shuttle Recovery Hearings, Apr. 29-30, 1987, vol. I, p. 64; also Larry Wear, MSFC). Some cite this as another case where a decision based on a constrained budget led to a less than optimal choice of technology for the long-term.

[50] Lockheed Space Operations Co. report to KSC: Liquid Rocket Booster Integration Study, LSO-000-286-1410, November 1988.

[51] This includes the first flight article and operations costs for the first flight.

LRBs could provide significant benefits in safety, performance, reliability, operations, environmental impacts, and the payload's physical environment, and offer important synergisms with other programs (table 3-2). However, they would also present higher risks, resulting from greater technical uncertainty, longer development times, potentially higher initial cost, and the need for launch pad modifications. Appendix A discusses the benefits and drawbacks of LRB development in more detail.

Develop Lightweight External Tank (ET)[54]

The emphasis on using improved materials in the Shuttle system has focused particularly on saving weight. For example, a 20 to 30 percent weight savings in the weight of the external tank could accrue from using aluminum-lithium (Al-Li)[55] alloy instead of the present aluminum alloy. If the external tanks were made of Al-Li and the intertanks (which hold the cryogenics) were made of graphite epoxy composite, the Shuttle would weigh 12,000 pounds less at lift-off. Because the external tank is carried nearly all the way to orbit, reducing the weight of the ET by 12,000 pounds would translate into almost 12,000 pounds of increased payload capability. Additional ET options, which could improve reliability and reduce costs, would involve increased use of robotics in manufacturing, nondestructive evaluation techniques, and thermal protection system improvements. Table 3-3 lists some typical materials improvements.

Table 3-2—Abort Mode Comparison of Shuttle/ Booster Configurations

Engine failure[a]		Abort mode		
Booster	+ SSME	SRB	ASRM	LRB
0	1	RTLS	RTLS	TAL
0	2	Split-S or ditch	Split-S or ditch	Loft-return
0	3	Split-S or ditch	Split-S or ditch	Loft-return
1	0	None	None	ATO
1	1	None	None	RTLS
1	2	None	None	Loft-return
1	3	None	None	Loft-return
2	0	None	None	TAL
2	1	None	None	RTLS
2	2	None	None	Loft-return
2	3	None	None	Loft-return

[a] Assumes engines fail at liftoff.

KEY: ASRM=advanced solid rocket motor; ATO=abort to orbit; LRB=liquid rocket booster; RTLS=Return to launch site; Split-S=aircraft landing maneuver that utilizes banking to dissipate energy and slow down; SRB=solid rocket booster; SSME=Space Shuttle main engine; TAL=transatlantic abort.

SOURCE: General Dynamics.

Improve Operations[56]

Introducing a number of new technologies and management strategies into Shuttle operations could make these operations more efficient, faster, and perhaps less expensive.[57] An excellent example of this is the Shuttle tile automation system described in box 3-C. NASA is also exploring the use of expert systems in Shuttle operations and making other efforts to "take people out of the loop" in order to reduce the number of human operations and decisions.[58] Its goals are to speed up Shuttle turnaround and reduce costs.

A POSSIBLE SHUTTLE IMPROVEMENT PROGRAM

To recapitulate, there are several options for conserving, maintaining, and improving the existing Shuttle fleet. The fleet could be conserved by flying fewer Shuttle flights to reduce the expected attrition

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[52] "The Case for a National Liquid Rocket Booster," General Dynamics Space Systems Division, March 1989.

[53] "U.S. Launch Vehicles—Planning for the Future," Rocketdyne, May 3, 1989.

[54] *Launch Options for the Future: A Buyer's Guide*, footnote 38, p. 29.

[55] There has been some concern as to the impact resistance of Al-Li, but as with any new candidate materials, extensive testing and certification would be done before any actual use.

[56] *Launch Options for the Future: A Buyer's Guide*, footnote 38, p. 29; *Reducing Launch Operations Costs: New Technologies and Practices*, op. cit., footnote 3.

[57] *Launch Options for the Future*, footnote 38, p. 29.

[58] Care must be exercised, of course, to not take this too far since many critical decisions require human judgment, based on the the best information available to the person at that time.

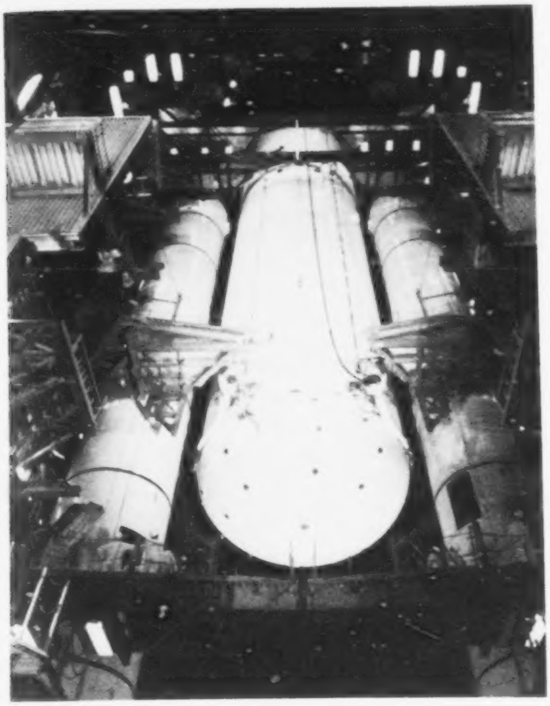

Photo credit: National Aeronautics and Space Administration

The external tank is lowered into place between the solid rocket motors in the Vehicle Assembly Building, Kennedy Space Center.

rate. To do this without reducing service, Shuttles could be modified to carry more payload, or complementary vehicles could be developed to fly missions that would otherwise require Shuttle flights. Shuttle fleet size could also be maintained, despite attrition, by ordering one or more additional orbiters now, as a hedge against attrition. If NASA waits until it loses an orbiter to order a replacement, the replacement might cost more and take longer to build than one ordered in the near future.

Table 3-3—Materials Improvements for Shuttle

External Tank:
- Use of robotics
- Nondestructive evaluation techniques
- Thermal protection system (TPS) Improvements/composite applications

Rocket Boosters:
- TPS development
- High temperature sealant development
- Process improvements
- Advanced Thrust Vector Control (TVC) System evaluation development

Solid Rocket Motors:
- Ablative and insulation process development and Nondestructive Evaluation techniques

Space Shuttle Main Engines (SSMEs):
- Use of robotics
- Weld improvements
- Producibility

SOURCE: Rockwell International Corp.

Table 3-4 lists several improvements discussed above, and some discussed in the OTA technical memorandum *Reducing Launch Operations Costs*, which could be elected to increase payload, safety, economy, or utility. The list is illustrative, not exhaustive, and contains entries (e.g., improved RSRMs, ASRMs, and LRBs) with redundant benefits, because having a variety of booster options may improve resiliency, and it may be desirable to have both an early improvement in payload capability and a larger improvement later.

A program of this magnitude could cost as much as $8.5 billion. A 10-year program would therefore require average funding of $850 million per year, some of which (e.g., for ASRMs) NASA has already planned to spend. However, to fund such a program at a level that would make a marked improvement in Shuttle system safety and performance would require finding extra space program funding, scaling down the Space Station program, or deferring other programs.

Box 3-C—Shuttle Tile Automation System

Inspecting the some 31,000 thermal protection system (TPS) tiles on the Shuttle orbiters and repairing damaged ones is highly labor intensive. Automating the inspection procedures could reduce overall labor costs, and increase inspection speed and accuracy. In 1986 NASA began the Space Systems Integration and Operations Research Applications (SIORA) Program as a cooperative applications research venture among NASA-KSC, Stanford University, and Lockheed Space Operations Company. One of its initial tasks is to apply automation and robotics technology to all aspects of the Shuttle tile processing and inspection system.

The team is developing an automated work authorization document system (AWADS) that will enable the technicians to document the condition of each tile, determine any necessary repairs or replacement, and generate work instructions. With the automated system, the computer, which is programmed to recognize each technician's voice, prompts the technician to find the correct tile, enter its number, and report on its condition in a systematic way. The TPS quality control technician first inspects the tiles after each flight and enters the part number, location, and condition of each tile into a computer database by voice. The computer's central database automatically generates a problem report in electronic format, which a TPS engineer uses to identify and recommend proper repair procedures for the tile. The problem report proceeds through an electronic signature loop until final approval for the repair. Finally, the TPS technician uses the voice data entry method to indicate tile status as repair procedures are completed.

The AWADS system and other automated systems developed in the SIORA program use the Ada programming language,[1] the software environment that will be used in the Space Station and other large NASA programs in the future. It offers the advantages of excellent portability from one hardware system to another, a rich set of programming functions and tools, and a uniform code documentation.

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[1] Ada was originally developed for use by the armed services. It has become the DoD software standard.

Table 3-4—A Possible Shuttle Improvement Program

Options	Cost	Benefit
Orbiter improvements:		
Develop alternate turbopumps for Space Shuttle main engines	\$228 million[a]	Safety and economy
Automate orbiter for unpiloted flight	\$200 million[b]	Safety
Extend orbiter flight duration	\$120 million	Utility
Built-in test equipment[c]	[?][c]	Safety and economy
Booster improvements:		
Increase thrust of redesigned solid rocket motor	\$50 to \$60 million	More payload
Continue to develop advanced solid rocket motor	\$1.3 to \$1.8 billion	Safety and more payload
Develop liquid rocket booster	\$3.5 billion	Safety and more payload
Other elements:		
Develop lightweight external tank	[?]	More payload
Complementary Vehicles:		
Develop Shuttle-C	\$1.5 billion	For cargo
Develop capsule or lifting body for Space Station escape	\$0.7 to \$2 billion	Safety

[a] Already funded by NASA.

[b] Only \$30M to \$40M for each additional orbiter.

[c] See OTA-TM-ISC-28, *Reducing Launch Operations Costs*.

NOTE: Most of these options would increase Shuttle payload capability, but by different amounts; their other benefits and their dates of availability would differ (see fig. 3-9). Therefore, two or more options might be pursued, for example, ASRMs to increase Shuttle payload capability and LRBs for increased safety and reduced environmental impact. On the other hand, NASA could develop complementary vehicles (e.g. Shuttle-C) to carry large payloads to orbit and reduce the Shuttle flight rate, reducing Shuttle fleet attrition. The United States need not decide imminently whether to proceed with one or more of these options. However, if such improvements are desired, more benefit will be reaped if they are begun earlier.

SOURCE: Office of Technology Assessment, 1989.

Chapter 4

Advanced Rockets

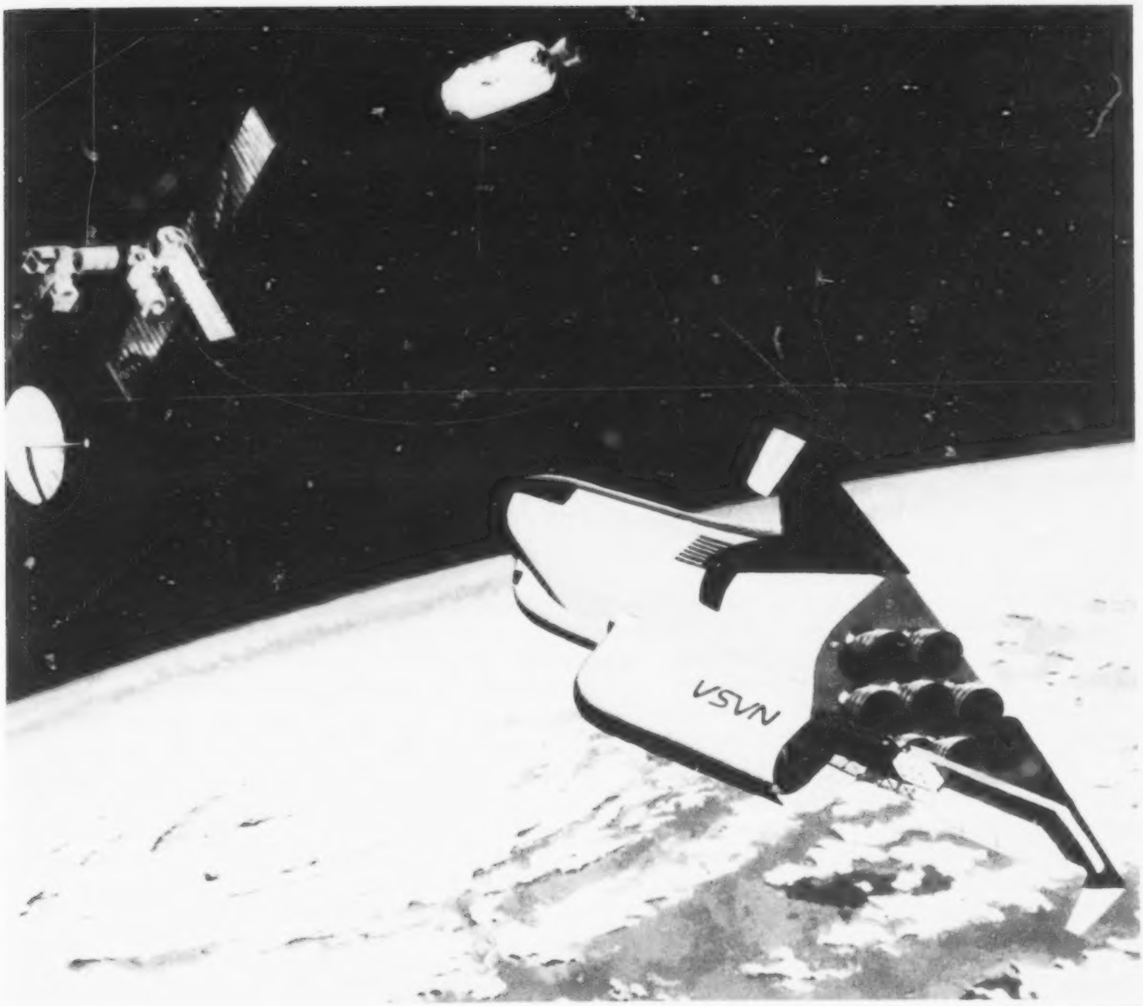

Photo credit: National Aeronautics and Space Administration

Artist's conception of one version of NASA's Advanced Manned Launch System Orbiter.

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Chapter 4

Advanced Rockets

INTRODUCTION

NASA is currently studying several proposed advanced crew-carrying launch systems that would help augment or supplant the current Shuttle fleet as it ages. They include the NASA Advanced Manned Launch System (AMLS—previously called Shuttle II), a Personnel Launch System (PLS), a crew-carrying version of the joint DoD/NASA Advanced Launch System (ALS), and a crew-carrying stand-alone Liquid Rocket Booster (LRB) system. NASA expects the AMLS to supplant the current Shuttle, but provide less payload capacity. The PLS or crew-carrying ALS could help augment the Shuttle if either is introduced before the Shuttle is retired. The intent of each concept is to provide for more cost-effective, reliable human access to space.

ADVANCED MANNED LAUNCH SYSTEM

NASA's Langley Research Center is leading the AMLS program, which will define advanced crew-carrying launch system concepts, including their development, system and operational characteristics, and technology requirements. The AMLS program could by the year 2005[1] lead to a vehicle significantly different than the Shuttle. NASA will compare the AMLS and the PLS with the option for an improved Shuttle, under study by the Johnson Space Center (JSC), and decide how best to proceed. NASA is evaluating five AMLS concepts (figure 4-1) listed below in order of increasing technological risk:[2]

- An *expendable in-line two-stage booster* with a reusable piloted glider.[3] This configuration at first appears similar to the U.S. Dyna-Soar[4] concept of the early 1960s, which would have been launched atop a Titan III, but would carry a larger crew. Dyna-Soar would have carried one or two pilots.[5] The European Space Agency and the Japanese NASDA have selected this approach for their spaceplanes Hermes and HOPE, respectively (see below). It might be possible to use an ALS to launch an AMLS orbiter.
- A *partially reusable drop-tank vehicle* similar to the fully reusable rocket concept described below, except that hydrogen propellants for the piloted orbiter are carried in expendable side-mounted drop tanks and the payload is carried in an internal canister. This configuration eliminates the need for a separate propulsion and avionics module seen in the next option, thus reducing its relative development and operations costs.
- A *partially reusable vehicle* with a glider atop a core stage, which has expendable tanks but recoverable engines and avionics. The core stage would be side-mounted on a reusable glideback booster. This partially reusable configuration may be economical at moderate launch rates.
- A *fully reusable rocket* with a piloted orbiter parallel-mounted (side-by-side) to an unpiloted glideback booster. This vehicle would be shorter than the in-line or glider atop a core stage version, making launch preparation easier. To facilitate payload integration or swap-

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[1] This tacitly assumes that the present Shuttle system, even with improvements and possible fleet additions, will be nearing the end of its useful life (as a result of wearout and/or attrition or cost reduction potential of new crew-carrying systems) between 2005 and 2010. Some argue that the present Shuttle system, having made its first flight in 1981, is still a relatively new aerospace system, and with well-considered improvements and additions to the fleet could serve effectively until the year 2020. In either case, a decision to proceed with an AMLS would not be required until at least 1995.

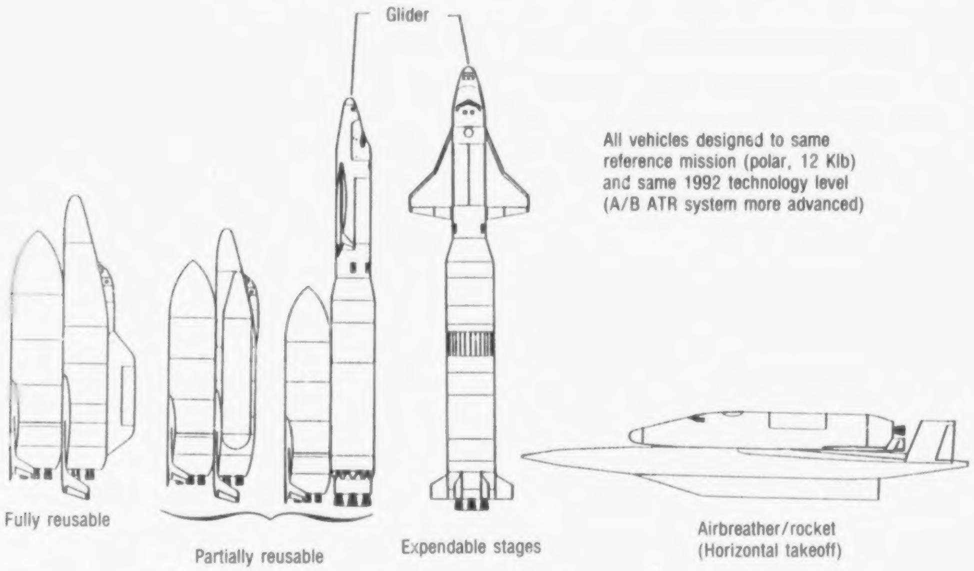
[2] And thus roughly in order of increasing initial development cost. Total life-cyle costs would vary greatly, however, depending primarily on reusability and flight rate.

[3] This vehicle could be very tall, making launch preparation difficult. Its design would depend on the booster selected and on the mission requirements of the orbiter. In addition, the orbiter engines could not be ignited on the launch pad prior to liftoff and must be fired in flight after stage separation, which would eliminate an abort mode on the ground. (An alternative that would remove this concern would be to require only an orbital maneuvering system in the orbiter, as in the Soviet shuttle and rely on the booster to place the orbiter in orbit.) Another obvious disadvantage is that this concept takes a step back from reusability.

[4] See ch. 5 of this report, or for a much more detailed description see "The Hypersonic Revolution—Eight Case Studies in the History of Hypersonic Technology," vol. I, case II, Richard P. Hallion (ed.), WPAFB, Ohio, 1987.

[5] The PLS concept could resemble the Dyna-Soar.

Figure 4-1—Advanced Manned Launch System Concepts



All vehicles designed to same
reference mission (polar, 12 Klb)
and same 1992 technology level
(A/B ATR system more advanced)

KEY: A/B = airbreather; ATR = air-turbo-rocket.

SOURCE: National Aeronautics and Space Administration, Langley Research Center.

ping, the orbiter would have a payload pod atop its fuselage, rather than an internal payload bay. The second-stage engines would be on the orbiter. Fully reusable configurations such as this are believed (but not proven) to minimize cost per launch at high launch rates. The fully reusable cryogenic tanks on both booster and orbiter are a critical technology requirement for this option.

- A *horizontal takeoff and landing air-breather/rocket*, which would resemble the German two-stage Saenger spaceplane (see later discussion in this chapter). This configuration would utilize the same technologies as for the AMLS rocket concepts summarized above, except that it would use an advanced air-turbo-rocket (ATR) air-breathing engine for the first stage. This vehicle would be fully reusable.

These alternate configurations also span a wide range of reusability. The higher the anticipated launch rate, the more attractive reusability becomes from the standpoint of cost.

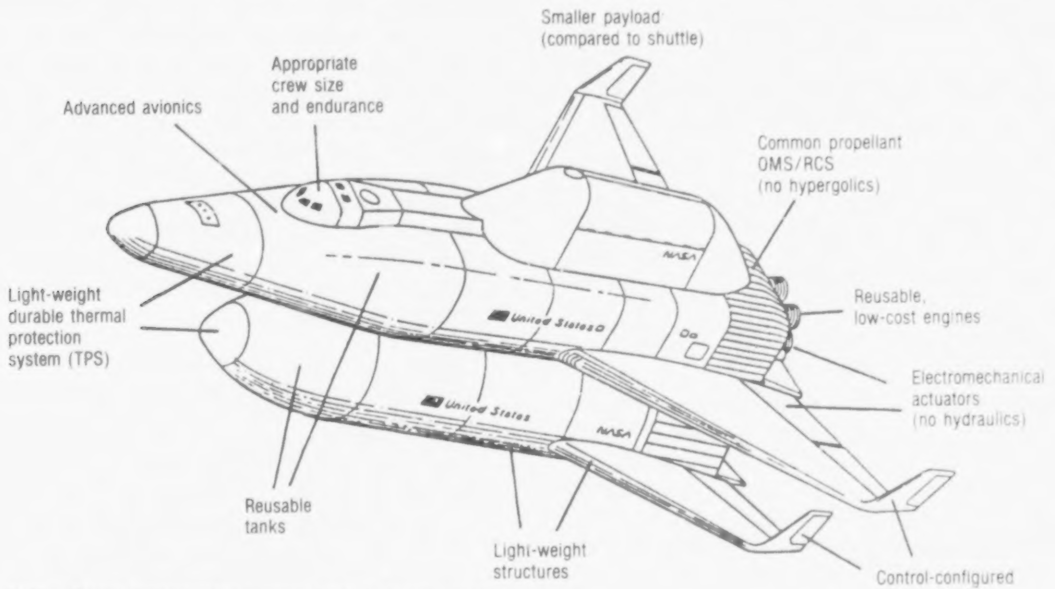
Because development of an AMLS vehicle need not begin until the mid to late 1990s, NASA could defer a decision on whether to start AMLS development until it has completed preliminary designs of alternative vehicles in sufficient detail to estimate technological risk and life-cycle cost.

Critical technology needs for all AMLS concepts include:

- light-weight primary structures,
- reusable cryogenic propellant tanks,
- low-maintenance thermal protection systems,
- reusable, low-cost propulsion,
- electromechanical actuators,
- fault-tolerant/self-test subsystems, and
- autonomous flight operations.

Figure 4-2 illustrates typical technology needs for a fully reusable version of the AMLS. Although meeting these advanced technology requirements would be challenging, none is considered a "showstopper." Thus, most experts feel that this technol-

Figure 4-2—Role of Technology in Advanced Manned Launch System (reusable version)



EY: OMS = Orbital maneuvering system; RCS = Reentry control system.

OURCE: National Aeronautics and Space Administration, Langley Research Center.

ogy could be available in time for an AMLS, since he AMLS would not be needed until after 2005.

PERSONNEL LAUNCH SYSTEM (PLS)

The Personnel Launch System is a new concept hat stems from "The Next Manned Transportation ystem" (TNMTS) study organized by NASA leadquarters. The TNMTS, a 2-year effort that egan in spring 1989, is now analyzing five primary pproaches:

1. purchase additional orbiters,
2. improve the current Space Shuttle system (Shuttle evolution),
3. develop a Personnel Launch System (PLS),
4. develop advanced rocket-powered launch vehicles (AMLS), and
5. develop advanced launchers based on air-breather technology.

JSC was named the lead center for the PLS option as well as for Shuttle evolution work. NASA's Langley Research Center will examine a lifting body option[6] for the PLS. The NASA centers, Marshall and Kennedy, would have major roles in developing a PLS but responsibilities for various tasks are still to be determined.

As the PLS concept is so new, little can be said about it, including its potential cost. It was prompted by the desire for a crew-carrying vehicle that could be available sooner than an AMLS and would also be cheaper and simpler. It could range from a small three- or four-person transport (similar to the space taxi and return concept described in ch. 6) to a vehicle sized to carry as many crewmembers as the present Shuttle.

A PLS vehicle could in principle be designed to be highly flexible and might also be configured to carry cargo as well as people. For example: it might be designed to carry small logistics payloads for the

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[6] See ch. 6 for descriptions of lifting bodies.

Space Station. It could also be designed to launch capsules capable of providing emergency rescue from the Space Station.

CREW-RATED ADVANCED LAUNCH SYSTEM

Several aerospace experts have suggested that should the United States decide to build the ALS, it would be prudent to give this vehicle the capability to launch people as well as cargo. If affordable, resilience[7] in human access to space is a desirable feature, since today people can only be launched on the Shuttle, which continues to be susceptible to major delays or loss from attrition.

The ALS Civil Mission Needs Statement requires that the ALS "provide a highly reliable (above 99 percent), fault-tolerant launch system capable of having a man-rated variant."[8] ALS stages or components could be used in an AMLS, and a crew-rated ALS launch vehicle could be used to launch a crew rescue vehicle (CERV—discussed in ch. 6) or alternatives to AMLS that have been proposed by industry (figure 4-3). Finally, it might be used to launch a PLS.

Current crew-rating procedures[9] require the use of greater strength margins in structural components, additional redundancy in subsystems, and added oversight and paperwork in the design, manufacturing, and operation of a launch vehicle compared to non-crew-rated vehicles.[10] Some officials in the ALS program, however, feel that the ALS would be so highly reliable and robust that the additional development cost or time required for crew-rating the ALS would be small. As proposed, the ALS, which could use all-liquid propulsion, would be designed for high reliability and would include such features as "engine out" capability (the ability to complete the mission even if an engine fails to operate), redundant electronics, and other high reliability features; and thus is intrinsically designed much like a crew-rated version.[11] At present, there is no "ALS crew-rating program" per se. Although the work statement for the ALS contractors does state that the ALS must "be capable of flying manned cargos," none of the contractors have yet found a need to identify different cargo or crew-carrying configurations.[12]

Along with improved resiliency, a crew-rated ALS would have three additional advantages:

1. if the crew-rated ALS were designed to carry a capsule like Apollo, crew escape could be easier than with the Shuttle, and escape could be possible during the whole trajectory, unlike the Shuttle from which escape is impossible during most phases of liftoff;
2. the crew-rated ALS could launch a crew-carrying PLS; and
3. there may be cases where it will be necessary to take personnel and cargo up to the Space Station but not down on the same mission. In that case, there is no need to risk an orbiter.

Redundancy in crew-rated launchers has many benefits, including improved resilience. But it would come at a cost. Policymakers would have to decide whether to saddle the ALS with the additional development and operating costs for crew-rating or

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[7] Having redundant launch systems (usually of different technological heritages) capable of accomplishing the desired mission so that if one launch system has to standdown, another can rapidly be used in its place.

[8] Thomas M. Irby, "Status of the ALS Program," *Proceedings of the Space Systems Productivity and Manufacturing Conference-V*, Aug. 16-17, 1988, El Segundo, CA. Another ALS Systems Requirement Document states that the ALS design "will not preclude human cargo" (Thaddeus Shore, SDIO).

[9] What makes a launch system "man-rated" is open to various interpretations. NASA is working on a consistent set of guidelines for crew-rating space systems. This document, still undergoing review, defines crew-rating as follows:

> A man-rated space system incorporates those design features and requirements necessary to accommodate human participants. This provides the capability to safely conduct manned operations, including safe recovery from any credible emergency situation. Man-rating is the process of evaluating and assuring that the hardware and software can meet prescribed, safety-oriented design and operational criteria. It is an integral part of the design, development, verification, management and control process. It continues throughout the operational life of the system.

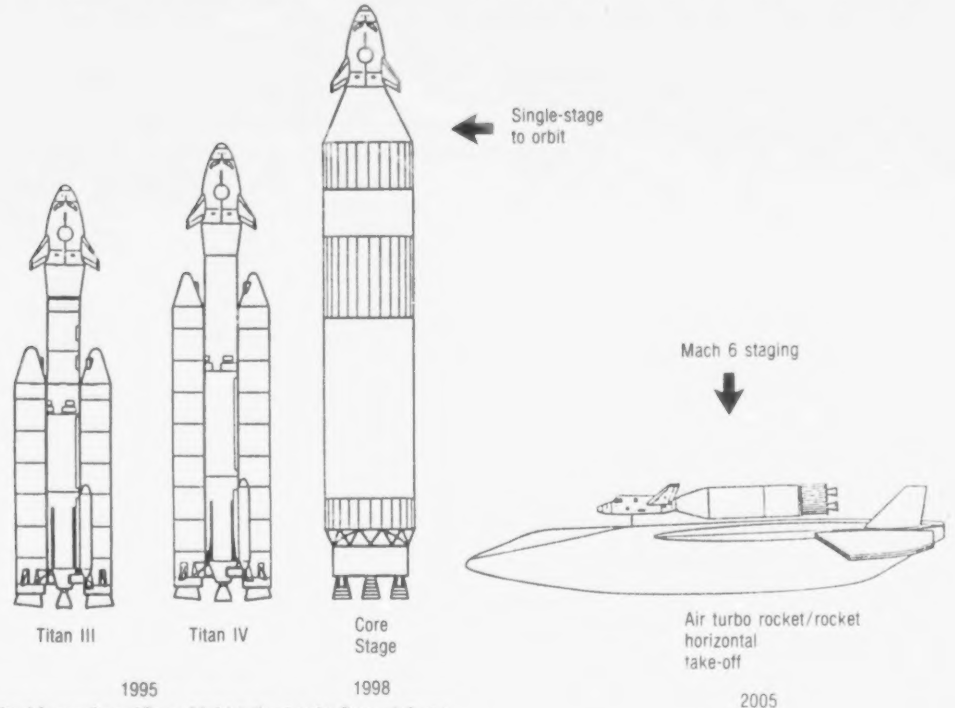
(*Guidelines for Man-Rating Space Systems*—Preliminary, Advanced Programs Office, NASA Johnson Space Center, JSC-23211, September 1988, p. 5.)

[10] This would also make it more difficult to reach the ALS goal of reducing vehicle and operations costs.

[11] For very high-value payloads, many argue that a vehicle should be crew-rated anyway.

[12] One concern of ALS designers is that g loads for the ALS may reach as high as 6 or 7, which is survivable by humans but not very comfortable. In contrast, the Shuttle is designed for a maximum of 3 g's.

Figure 4-3—Crew Emergency Rescue Vehicle (CERV)/Space Taxi and Return (STAR)



SOURCE: National Aeronautics and Space Administration, Langley Research Center.

whether resilience would be better served by a PLS or a stand-alone LRB system.

STAND-ALONE LRB SYSTEM

If LRBs were developed as part of a Shuttle solid rocket booster replacement program, or in conjunction with an ALS engine program, these boosters could be used to propel a stand-alone system capable of carrying people to orbit. Because the engines would have already been developed, a launch system built around an LRB could be cheaper to develop than an entirely new launch system.

FOREIGN CREW- AND PASSENGER-CARRYING VEHICLE PROGRAMS

The United States and the Soviet Union are currently the only nations capable of sending people to and from space. The Soviet Union has recently developed a reusable space shuttle orbiter that is launched on its heavy-lift launcher, *Energia*.

The European Space Agency (ESA), Japan, the Federal Republic of Germany, and the United Kingdom are all in various stages of developing their own reusable launch systems, some of which, if successful, would be capable of transporting humans to orbit. The designs for these launch systems still exist largely on paper. Nevertheless, these countries possess a high level of technological capability and could develop crew-carrying vehicles if they wished to make the necessary investment. For these countries, building launch systems has become an important part of decreasing their dependence on the United States and the Soviet Union for reaching space. Developing crew-carrying capability would be a national achievement signaling their status as major space powers, able to develop and use a broader range of advanced technology.

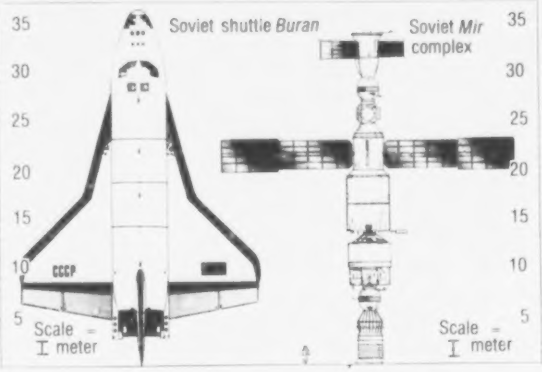
Non-U.S. concepts differ widely as to configuration, reusability, crew size, and payload capability, and their project status ranges from preliminary design, like the Hermes, to the Soviet *Buran*, which has already completed its first test flight. Except for the Soviet shuttle, none of these systems yet pose a competitive challenge to the United States. The United States should monitor the progress of these programs both for competitive concerns and cooperative opportunities in order to respond appropriately.

Soviet Space Shuttle

The Soviet counterpart to the U.S. Space Shuttle made its maiden flight on November 15, 1988. Lifted into space by an *Energia* booster (presently the world's largest booster), the 100-ton shuttle named *Buran* (Snowstorm) remained aloft for two orbits of the Earth, some 3 hours and 25 minutes. The spacecraft is nearly identical in physical shape to that of its American cousin (see figure 4-4), but it does exhibit several key differences. The primary difference is that *Buran* lacks its own main engines, relying instead on propulsion provided by the *Energia* to place the shuttle craft into orbit. *Buran* also uses a set of small maneuvering thrusters to reach orbit and later deorbit.

Similarities between the U.S. and Soviet designs are striking. The delta wing, vertical tail structure, payload bay, window placement, as well as thermal protection patterns are common to both vehicles. Initial reaction from Western experts held that the identical profile of the two spacecraft had saved the Soviets years of development time and expense by copying U.S. plans. Soviet space engineers claim the similarity derives from the same mission objectives of both craft: ferrying people and payloads into Earth orbit and maneuvering from space to a runway landing. Soviet reports state the *Buran* can place 66,000 pounds of payload into orbit and return from space with 44,000 pounds.[13] The Soviets claim that special-purpose missions using *Buran* can last up to 30 days. Eventually, four flights per year are envisioned using these shuttle vehicles.

Figure 4-4—Soviet Space Shuttle *Buran* and *Mir* Space Station



SOURCE: Teledyne Brown Engineering.

In some respects, the *Energia-Buran* is more versatile than the U.S. Shuttle. For example, the *Energia* rocket can launch an orbiter, or it can be launched without an orbiter, in which case it can carry a payload weighing more than 220,000 pounds. It has four reusable first-stage boosters clustered around an expendable second ("core") stage, which has four engines. First- and second-stage engines are ignited on the launch pad, and, because all engines use liquid fuel, they can be shut down on the pad or in flight to abort a launch if one or more fails to achieve sufficient thrust. In some cases the orbiter may still reach orbit, even if an engine has been shutdown during flight. In any event, the vehicle is expected to maintain controlled flight—to an emergency landing site if carrying crew, or to a place where it can ditch or crash without endangering people or structures.[14]

Perhaps the most interesting feature of the Soviet approach to winged space flight is the Soviet ability to use automated landing systems. *Buran's* first flight was unpiloted and relied on ground controllers for on-orbit maneuvering. *Buran* then used onboard computers to carry out an automatic approach and landing at a special shuttle runway at Baikonur.[15] Three parachutes slowed the shuttle vehicle to a stop.

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[13] To a 100-nmi high orbit; see U.S. Department of Defense, *Soviet Military Power*, 1988.

[14] G. Gubanov, *Pravda*, July 30, 1988, 2d ed., p. 4. [in Russian]

By contrast, although the U.S. Shuttle fleet does carry some automated landing equipment,[16] astronauts to date have vetoed its use below a certain altitude. The Soviet technology used for *Buran's* automatic flight ability appears to be coupled to the hardware developed for the Tu-204, a new Soviet medium-range twin turbofan aircraft.

Reports remain sketchy as to overall capabilities of the Soviet shuttle design. Six Soviet shuttlecraft are believed to be in various stages of construction. Another shuttle, named *Ptichka* (little bird) is expected to be launched next. As many as 10 individuals can be accommodated in the *Buran* shuttle, Soviet experts have stated.

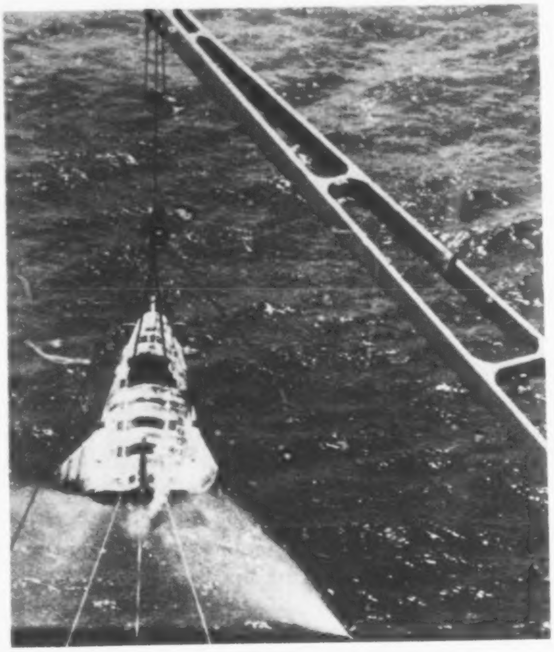
The Soviets have modified MiG 25 ejection seats for use in its space shuttle when it makes a piloted flight. Soviet engineers state that the ejection seats can even be used when the shuttle is on the launch pad. The maximum speed at which they can be used is Mach 3.[17]

Soviet Spaceplane[18]

Still an enigma to the United States is the Soviet Union's subscale prototype spaceplane and what part it plays in their space program. This 1-ton winged mini-spaceplane (see figure 4-5) in its first four flights between 1982 and 1984 orbited Earth only once and touched down in water. It has by now possibly made a dozen flights.

The Soviet mini-spaceplane program resembles the effort undertaken in the 1960s in the U.S. Dyna-Soar program, and the European Hermes project presently underway. Some U.S. experts speculate that it was designed to evaluate the aerodynamic and reentry characteristics of the much larger Soviet shuttle. Others theorize that the plane could be built for quick launch and turnaround, as well as for occasional reconnaissance. A full-scale spaceplane, capable of runway landings, is expected to fly with two to three cosmonauts, launched by the SL-16 booster. Some experts have hypothesized that the spaceplane could serve as a crew escape vehicle attached to the Soviet *Mir* space station.

Figure 4-5—Soviet Spaceplane



SOURCE: Royal Australian Air Force.

European Space Agency Hermes Spaceplane

This piloted shuttle has been championed by France as an effort to provide an independent, European, crew-carrying launcher. As a small, winged spaceplane 15 meters long with a wingspan of 10 meters, Hermes could carry a crew of three and slightly over 2 tons of payload to a 500-km orbit. The spaceplane itself originally was meant to be completely reusable but as now envisaged, the vehicle will have an expendable adapter called the Hermes Resource Module that will separate from the spaceplane and burn up during reentry. Current mission planning calls for an initial unpiloted test launch on an Ariane 5 in early 1998, crew-carrying flights beginning in late 1998 or early 1999, and regular operational flights twice annually starting in 1999 or 2000. Total development cost for the Hermes project is estimated at over $4.5 billion,[19] with most of the financing coming from France and the Federal Republic of Germany. Two vehicles would initially be built, leading to an eventual fleet of four. Each Hermes could make two to three flights per year. One recent Hermes concept is shown in figure 4-6.

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[15] Recently, the Soviets have expressed concerns about their automatic systems, and cite this as one reason for delaying the next flight (which will carry no crew) until 1991. The first crew-carrying flight may not occur before 1992.

[16] The U.S. Shuttle is not fully automatic as pilots must brake and steer it on landing. Automating these tasks has been proposed, however—see ch. 2.

[17] *Space*, January-February 1989, p. 56.

[18] Peter M. Banks and Sally K. Ride, "Soviets in Space," *Scientific American*, February 1989.

Japanese HOPE

The Japanese National Space Development Agency (NASDA) is studying a concept called "HOPE" (H-II Orbiting Plane), an unpiloted winged mini-shuttle. HOPE would be launched atop the Japanese H-II launch vehicle, an indigenously designed and built expendable rocket, expected to fly in 1992 (see figure 4-7).

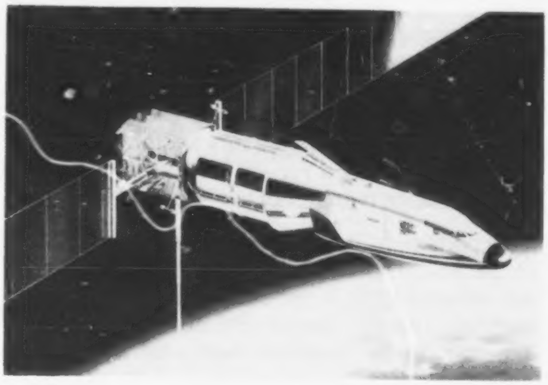
Japan is considering HOPE for several missions, such as delivery and return of materials from the Japanese Experiment Module (JEM) of the international Space Station, polar-orbital missions, and what the Japanese call "space technology experiments." The HOPE design still is emerging but current plans call for it to land horizontally. NASDA suggests a first flight date in late 1996.[20]

HOPE actually may be Japan's first step toward an autonomous piloted spaceflight capability early in the 21st century. A national "Advisory Committee on Space Plane" recommended a broad research and development plan for a fully reusable aerospace plane. The committee urged that the Space Plane "be promoted as an important national R&D project," but promised that the program would be opened to international cooperation in its early stages.

German Saenger

The Federal Republic of Germany is studying this two-stage launch vehicle (figure 4-8), which would be a piloted craft carrying a cargo plane piggyback into space. Stage 1 would be a large hypersonic aircraft propelled by six hybrid turbo-ramjets and would be designed to take-off and land horizontally at several large European airports. For flights without a crew, the second stage would be of an expendable cargo upper stage ("Cargus"), capable of placing 33,000 pounds into LEO or 5,500 pounds into GEO. Cargus would use a single LOX/LH2 engine, the same powerplant being developed for the Ariane 5 core. For piloted flights, a spaceplane called "Horus" (Hypersonic Orbital Upper Stage) would serve as Saenger's second stage. Its present configuration gives it the same basic shape as Hermes with twice as much volume. Designers plan for Saenger to operate as a ferry craft with limited orbital duration—perhaps not more than 1 day. Horus could lift 4,000 to 6,000 pounds of cargo, plus two pilots and four passengers to a 270-mile orbit at a 28.5-degree inclination. Horus would use two LOX/LH2 engines similar in size to the U.S. Shuttle's SSMEs.

Figure 4-6—European Space Agency Hermes Spaceplane



SOURCE: European Space Agency.

A major incentive for developing Saenger is the potential reduction in space transportation costs. The West German Research Minister states that, in theory, Saenger has the potential of reducing the costs of placing payloads into orbit from about $3,500 per pound to $500 per pound. Recently, the

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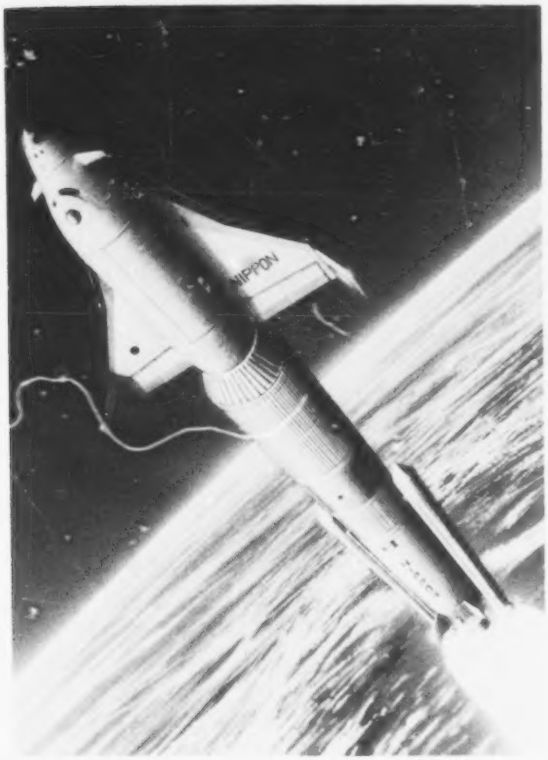
[19] "Canada Joins Hermes Program," *Aviation Week and Space Technology*, Mar. 13, 1989, p. 30.

[20] Stanley W. Kandebo, "Japanese Refining Unmanned HOPE Orbiter for Planned 1996 Launch," *Aviation Week and Space Technology*, Apr. 3, 1989, pp. 57-58.

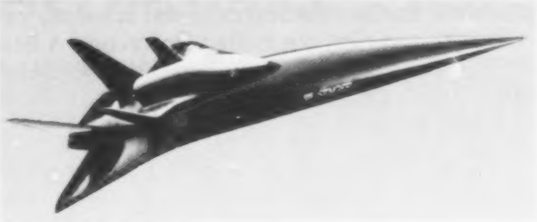
Figure 4-7— Japanese HOPE



SOURCE: Japanese National Space Development Agency.

German Government agreed to fund the initial development work for Saenger with a first demonstration of components between 1993 and 1999. The prototype could be finished by the turn of the century. Development work carried out through the European Space Agency (ESA) could begin as early as 2004. For the first phase, which will run to the end of 1992, the West German Research Ministry is providing $122 million, 7 percent of its total budget for space activities. The German Aerospace Research establishment is contributing $48 million, and the German Research Society $17 million. A further $22 million is being invested by the West German aeronautics and space industry for a total initial commitment of $209 million.[21]

Figure 4-8—Federal Republic of Germany Saenger II



SOURCE: Messerschmitt-Bölkow-Blohm GmbH, Space Systems Group

United Kingdom Hotol

As early as 1978, British Aerospace Corp. began studying the prospects for lowering the cost of satellite launchings by 80 percent. Out of these studies, and revolving around a new engine proposed by Rolls-Royce, British Aerospace drafted plans to develop Hotol, a fully recoverable and reusable unpiloted launcher capable of taking off and landing from a runway and reaching orbit with a single stage (figure 4-9).

The heart of the project is Hotol's propulsive power, the still-secret Rolls-Royce RB-545, called the Swallow engine. This radically new hybrid rocket engine is designed as a dual-rotor motor, first burning onboard liquid hydrogen while liquefying oxygen as the vehicle moves through the Earth's atmosphere. Above the atmosphere and on into orbit, the engine then uses onboard liquid oxygen to burn the fuel. This engine concept would halve the amount of liquid oxygen required to be carried at takeoff thus dramatically reducing the weight of the craft compared to one using a conventional booster.

Hotol is designed to reach orbital velocity at a height of 90 km. The craft would then coast into a stable operational orbit of about 300 km. The design goal is to deliver 7 to 11 tons into low-Earth orbit at a cost of $300 per pound. Hotol is designed to operate without human crews aboard for most missions, although a pressurized habitable module could be situated in the payload bay to support astronauts, not as pilots, but in an "executive role."

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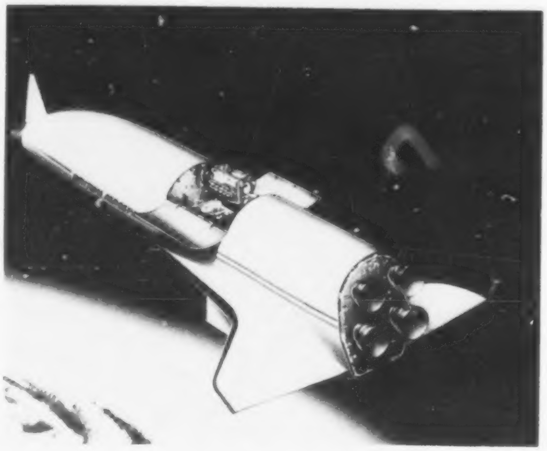
[21] Don Kirk, "Germany Enters Hypersonic Race," *Science*, vol. 243, Mar. 10, p. 1284, 1989.

Hotol mission scenarios call for the vehicle to launch and recover satellites, service space stations and platforms, conduct microgravity and scientific experiments, and carry out military operations. A fleet of 5 vehicles was planned, each with a 120-mission design life. Hotol's recurring launch cost was estimated at just $5 million.

Hotol design teams completed a 2-year, $4 million proof-of-concept study in late 1987. They outlined a follow-on "enabling technology" program that would lead to a development start in 1994 and a first flight by Hotol near the year 2000. Despite the momentum built up by British Aerospace and Rolls-Royce, the U.K. Government, in July 1988, refused to provide a requested $9 million per year for 3 years to continue Hotol's research and development. The two firms were to match the government funding made available through the British National Space Centre. Hotol's future may depend on international participation but this would require declassification of the Swallow engine, something that the British have been loath to do.

Figure 4-9—United Kingdom Hotol



SOURCE: British Aerospace.

Chapter 5

The National Aero-Space Plane

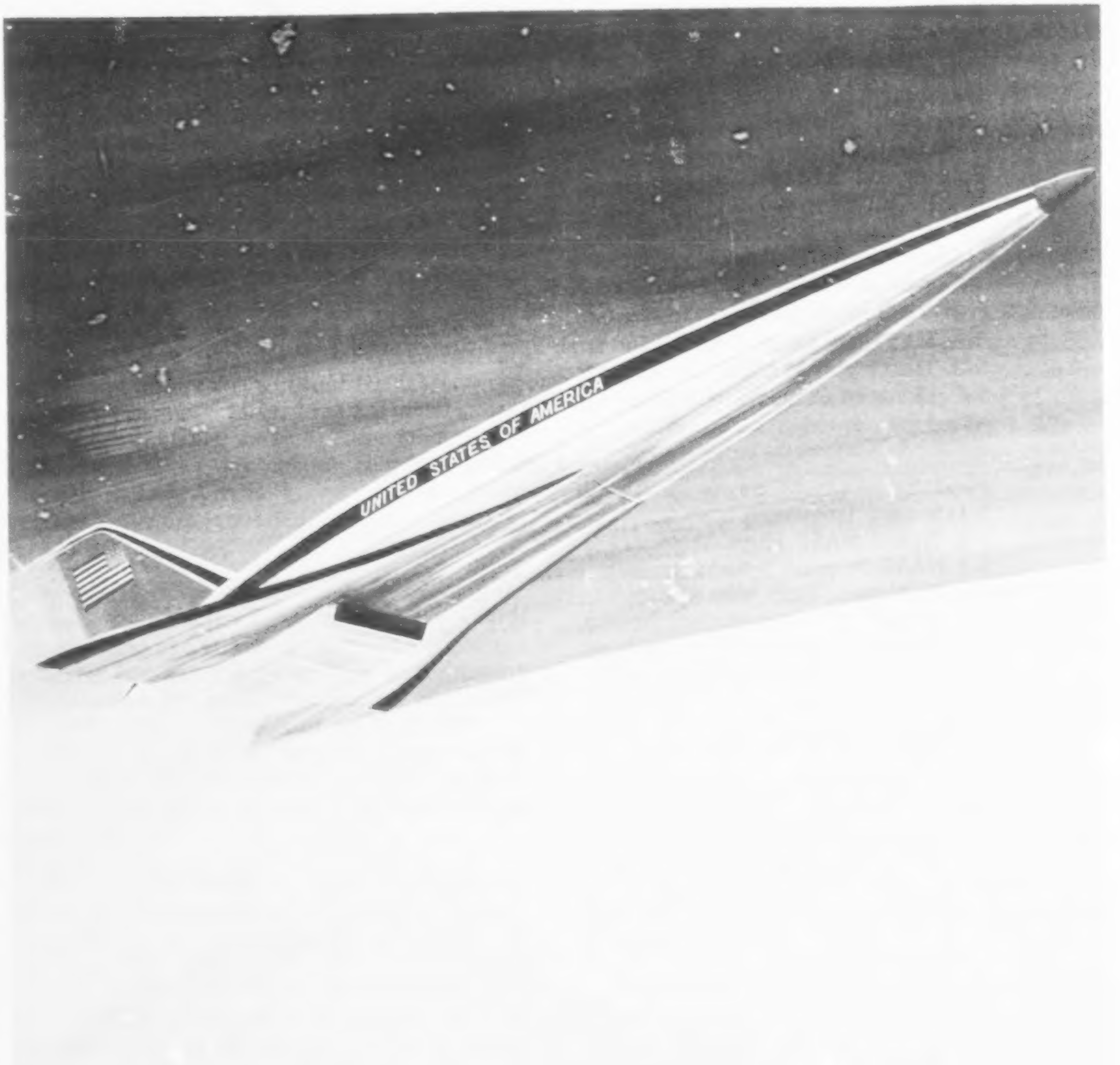


Photo credit: National Aero-Space Plant Joint Program Office

Conceptual design for the X-30 National Aero-Space Plane.

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Chapter 5

The National Aero-Space Plane

INTRODUCTION

The National Aero-Space Plane (NASP) program is a research effort funded by the Department of Defense (DoD), the National Aeronautics and Space Administration (NASA), and industry to develop and demonstrate the technologies of hypersonic[1] flight in a revolutionary, piloted research vehicle designated the X-30. If successful, the X-30 would demonstrate the capability to reach outer space using a single propulsion stage that would make unprecedented use of air-breathing engines.[2] In a launch demonstration that program officials hope to complete by October 1996, the X-30 would take off horizontally from a conventional 10,000-foot-long runway, accelerate to Mach 25 in the upper atmosphere, enter orbit, and return to Earth, landing on a conventional runway. In contrast, a typical rocket launcher ascends vertically from special launch facilities and jettisons one or more propulsion stages during flight.

The NASP program is currently developing the technology to build the X-30. Although the X-30 is meant to serve as a technology test-bed and not as a prototype, it is being designed as a demonstration vehicle that could resemble prospective operational launch vehicles. Proponents of the X-30 believe it could herald a new era in flight, spawning military and civilian aircraft capable of global range at hypersonic speeds, or low-cost and routine access to space.

OTA included NASP in its assessment of advanced space transportation technologies because of the possibility that operational vehicles of utility for both the civilian and military space programs may evolve from the X-30. These "NASP-derived vehicles" (NDVs) would offer a radically different approach to space launch and might eventually become important elements of a future space transportation system, ferrying people or cargo into low-Earth orbit with rapid turn-around and low cost. Depending on its eventual configuration and payload-carrying capability, it is conceivable that a NASP-derived vehicle might also supplement or replace the Space Shuttle when the Shuttle fleet reaches the end of its useful lifetime.

Program officials believe that an aerospace plane could lower the cost to reach orbit because its design would allow:

- rapid turn-around;
- manpower support at commercial aircraft levels (in contrast to Shuttle operations);
- complete reusability of the system with minimal refurbishment between flights;
- operations from conventional runways; and
- greater payload fractions,[3] the result of using air-breathing, rather than rocket engines.

Not all of these potential economies would be unique to NASP-derived launch vehicles; some could also be realized in other advanced launch systems.

Although this chapter refers often to vehicles derived from technologies developed in the NASP program, neither the construction of an X-30 vehicle nor a follow-on program to build an operational vehicle has been funded yet. A decision by a DoD/NASA Steering Group on the feasibility of moving beyond the current technology development phase to construct a flight vehicle is now scheduled for September 1990. As the later section, *Policy and Options* explains, recent revisions in the DoD budget submission for fiscal year 1990, if adopted by Congress, would have a dramatic effect on the direction of even the research portion of the NASP program.

OTA did not perform a detailed evaluation of the economic benefits of the NASP program or NASP-derived vehicles, nor did it attempt to evaluate the potential contribution of the NASP program to the Nation's defense or its defense technology base. However, NASP officials believe that these contributions would be among the most important benefits of their program. The broader implications of the NASP program are beyond the scope of this report and are considered only in so far as they affect the support, schedule, cost, and likelihood of achieving an operational launch capability. This report presents an overview of the NASP program, a short introduction to the technologies of hypersonic flight, and a guide to the issues likely to be faced by Congress as the program nears the point where it could move beyond its current research stage.

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[1] Hypersonic usually refers to flight at speeds of at least Mach 5—five times the speed of sound, or about 4,000 miles per hour. The speed of sound in dry air is 331.4 meters per second (742.5 miles per hour) at a temperature of 0 degrees Celsius (273 degrees Kelvin).

[2] Air-breathing engines burn atmospheric oxygen during combustion instead of carrying an oxidant internally as is typical on rockets. All conventional aircraft engines are air-breathers.

[3] Payload fraction is the weight of the payload expressed as a fraction of the launch vehicle's gross lift-off weight, including fuel.

BACKGROUND

The X-30 requires the synergism of several major technology advances for success. The propulsion system is based on experimental hydrogen-fueled, supersonic combustion ramjet ("scramjet") engines. A scramjet is designed to allow combustion to occur without slowing the incoming air to subsonic speeds, as is typical in all other air-breathing engines. Ground tests of scramjet engines indicate that they could propel an aircraft to hypersonic speeds, but the X-30 would be the first aircraft to explore fully their potential in flight.

The X-30 airframe would require extremely lightweight and strong structures, some capable of withstanding temperatures thousands of degrees hotter than materials currently used in aircraft construction. In contrast to the thermal protection tiles used on the Space Shuttle, some of the X-30's high-temperature tolerant materials would be formed into load-bearing structures. In addition, while some of the X-30's materials, such as carbon-carbon composites, have been used before (although not as load bearing structures), others are still in a laboratory stage of development. Furthermore, even with special materials and coatings, novel cooling techniques would be necessary to keep some leading edges and internal engine parts at tolerable temperatures. The active cooling system would also be used to recover fuel energy that would otherwise be lost as heat. The use of "regenerative" cooling techniques has never been attempted in an aircraft, although the technique is commonly employed in liquid rocket engines. Developing the instrumentation and control system of the X-30 also presents unique technical challenges.

The X-30 would make unprecedented use of numerical aerodynamic simulation as a design aid and as a complement to ground-test facilities that are unable to reproduce the full range of conditions the X-30 would encounter in hypersonic flight. The NASP program is currently utilizing a substantial fraction of the U.S. supercomputer capability in what officials describe as a massive effort to advance the state-of-the-art in the computational techniques needed to design the X-30. In fact, the dependence on supercomputers and numerical simulation models of hypersonic flight is so great they constitute a key "enabling" technology for the X-30, rivaling propulsion systems and materials in importance.[4]

The requirement that aircraft structures be lightweight, reusable, and able to withstand thermal cycling (heating and cooling) over multiple flights stresses all aspects of vehicle design. In addition, the engine, airframe, cooling systems, and control systems would all be melded together in the X-30, thus creating unusual challenges for both vehicle designers and program managers (figure 5-1). For example, the airframe and engine cannot be developed independently; instead, they must be designed from the *outset* as a single package. The heat load on the X-30 will be a sensitive function of both the vehicle's aerodynamics and of the heat generated by engine combustion. In turn, the thermal requirements affect materials and structural requirements. Finally, aircraft instrumentation and control systems must be matched to airframe designs, which are coupled to propulsion and thermal control systems.

OPERATIONAL VEHICLES

Even if the NASP program proves completely successful, an additional program would still be necessary to develop operational vehicles. The extent of such a program would depend on how well technology issues are resolved by the X-30 and how much modification would be necessary for first-generation follow-on vehicles. Safety, crew escape, environmental compatibility (pollution and noise),

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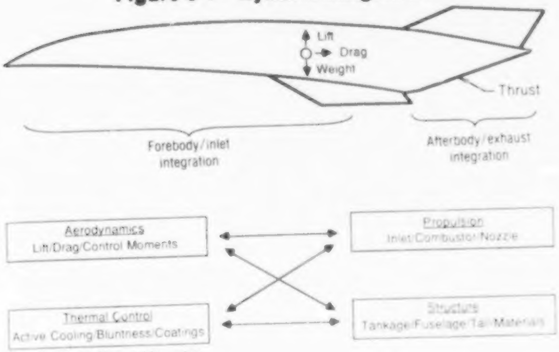
[4] The enabling technologies of NASP were critically reviewed in *Hypersonic Technology For Military Application*, Committee on Hypersonic Technology for Military Application, Air Force Studies Board, National Research Council (Washington DC: National Academy Press, 1989) and *Report of the Defense Science Board Task Force on the National Aerospace Plane (NASP)* (Washington DC: Office of the Under Secretary of Defense for Acquisition, September 1988). See also *National Aero-Space Plane: A Technology Development and Demonstration Program to Build the X-30* (U.S. General Accounting Office Report GAO/NSIAD-88-122, April 1988).

Figure 5-1—System Integration


Lift
Drag
Weight
Thrust
Forebody/inlet integration
Afterbody/exhaust integration
Aerodynamics
Lift/Drag/Control Moments
Propulsion
Inlet/Combustor/Nozzle
Thermal Control
Active Cooling/Bluntness/Coatings
Structure
Tankage/Fuselage/Tail/Materials

SOURCE: **McDonnell Douglas.**

production costs, maintenance costs, and the capability for rapid turn-around on a routine basis would all have to be addressed in engineering an operational vehicle. A true operational capability also presumes that the problems of pilot training, maintenance, logistics, and support for the vehicle (including hydrogen handling and storage capability) have been solved. For a military vehicle there is the additional issue of integrating the vehicle into the existing military force structure.

The detailed characteristics of operational launch vehicles that might follow the X-30 are classified. According to program officials, the first-generation of vehicles would not be expected to carry Shuttle-class payloads, although later variants might. How much of the vehicle's gross take-off weight could be devoted to payload would depend on the success of the NASP material and structures development program and the actual engine performance.

The NASP Joint Program Office (JPO) is evaluating a concept for a vehicle about the size of a McDonnell Douglas DC-10 that would be able to carry 20,000 pounds to the low-Earth orbit of the proposed Space Station. In general, a vehicle designed with a larger wingspan, more fuel, and more powerful engines can carry a heavier payload, but there are practical limits. As vehicle weight rises, propulsion requirements become more difficult to meet. Heavier vehicles also place more stress on landing gear and brakes. In addition, take-off and landing from conventional-length runways becomes difficult as vehicle weights rise. Finally, vehicle costs rise, especially if the vehicle is constructed with expensive specialized materials.[5] NASP designers have announced that they are striving for NDV vehicle weights close to 400,000 pounds.[6]

In contrast to a launch vehicle, which would fly directly to low-Earth orbit in about 30 minutes, a hypersonic cruiser might fly for several hours at speeds and altitudes of, for example, Mach 5-14 and 80,000 to 150,000 feet. Using hydrogen as fuel, its range would extend to intercontinental distances. Figure 5-2 compares the trajectory of the Space Shuttle with representative trajectories for an aerospace plane carrying out orbital or hypersonic cruise missions.[7] The NASP effort to develop hypersonic cruise vehicles has sometimes been confused with proposals to develop a commercial hypersonic transport. At present, the vehicles being studied by the NASP JPO *do not* include a commercial hypersonic transport or "Orient Express." Moreover, the least costly path to the development of such a vehicle would not be via the development of a Mach 25 aerospace plane (see box 5-A).

The relaxed speed requirement makes the design of a hypersonic cruiser less challenging than a Mach 25 orbital vehicle, but extended hypersonic flight within the atmosphere would place a much larger demand on thermal cooling systems (the orbital vehicle experiences a higher peak thermal load than the cruiser but it is for a much shorter duration). Thus the optimum airframe for a hypersonic cruiser would differ in design from a single-stage-to-orbit (SSTO) vehicle, and it is likely that operational versions of these vehicles would each require a separate development program.

Preliminary projections by NASP contractors of the operating and support costs of an NDV with a

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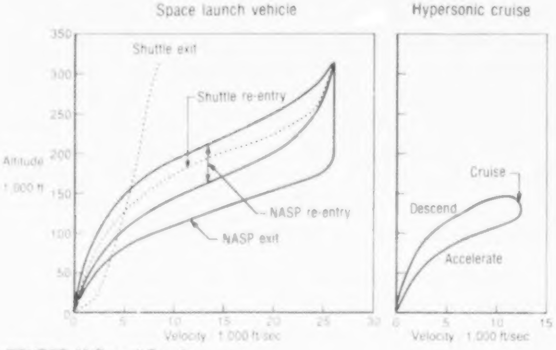
[5] However, according to the NASP JPO, the estimated cost to increase the X-30's baseline payload by even a factor of four would still be only a small fraction of the total development cost for the vehicle.

[6] Douglas Isbell, "NASP, International Space Trade Highlight Symposium," *Washington Technology*, Apr. 20-May 10, 1989, p. 20.

[7] Maneuvering at hypersonic speeds has some surprising consequences. For example, a turn at hypersonic speed can take an aircraft over a sizable portion of the United States. A pilot in the X-30 making a 2g (one g is the acceleration due to gravity) turn at Mach 10 would travel over a track that would take him from Edwards AFB, California to Denver, Colorado. A Mach 15 turn at 2 g would take the pilot over a ground track from Edwards to Chicago.

Figure 5-2—Typical NASP Flight Trajectories



SOURCE: McDonnell Douglas.

payload capability to low-Earth orbit of 65,000 pounds (likely to be a second-generation NDV) range from $1 million to $9 million per flight, exclusive of development or production costs. In terms of mass to orbit, the maximum cost of placing payloads into low-Earth orbit was estimated at $140 per pound. Achieving these remarkably low costs (one to two orders of magnitude improvement over the Space Shuttle)[8] would, among other things, require rapid turn-around and full reusability.

Rapid turn-around would allow high-rate operation and lower unit launch costs, in part because nonrecurring costs could be spread over a larger number of missions. However, to realize these economies of scale presupposes that sufficient missions exist to support the higher volume operations. In addition, maintenance costs between flights costs would have to prove to be as low as predicted.[9]

A rough extrapolation from the projected X-30 costs indicates that potential unit costs of an operational launch vehicle could be on the order of $1 billion in addition to the costs of research, development, testing, and evaluation.[10] Predictions of the development costs for an operational vehicle are very uncertain at present because they extrapolate from preliminary cost estimates for the X-30. Research and development costs for Shuttle components through 1984 totaled approximately $15 billion[11] ($18 billion in current dollars), however, NASP officials believe development costs for operational vehicles derived from the X-30 would be less. Whatever the actual costs, it is clear that a substantial commitment from DoD or NASA would be necessary to build a fleet of launch vehicles.

X-30 DESIGN GOALS

As an experimental vehicle, the most important function of the X-30 would be to serve as a flying test bed where synergistic technologies—propulsion, materials, structures, thermal control, guidance, and flight instrumentation—could be combined and proved. In particular, the X-30 would effectively function as a "flying wind tunnel" for high-Mach scramjet propulsion that cannot be completely validated using only ground-based facilities and computer-based simulation.

Many important characteristics for the X-30 have not been made public. These include size, weight, and vehicle payload. However, NASP officials have stated that the X-30's size would be between that of a Boeing 727 and a McDonnell Douglas DC-10, and it would carry at least several thousand pounds of instrumentation. The actual size and weight of the X-30 would depend on many factors, including the final airframe and engine design and the required

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[8] For a detailed discussion of Shuttle costs see ch. 7 and app. A of U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988).

[9] Achieving rapid turn-around would demonstrate that little maintenance is required, provided maintenance is not simply shifted from the flight line to the depot, and provided the maintenance man-hours per sortie remains low over the life of each vehicle. Moreover, average vehicle service life must meet or exceed the design service life of 150 sorties (to orbit) if the average cost per launch is to be as low as predicted by estimates based on this assumption. Note too that should payload costs come to exceed mission expenditures, the importance of reducing launch costs would be diminished.

[10] This figure is meant to be illustrative—it is *not* based on any cost estimation model. Reliable cost estimates for an NDV cannot be made until an X-30 is built and flight tested. Even then there would be uncertainties in life-cycle costs. The cost to deliver the new Space Shuttle orbiter Endeavour (OV 105) in 1991 is expected to be more than $2 billion. However, this increase in cost over previous orbiters represents the expense of incorporating new safety and other improvements, and restarting production lines.

[11] A comprehensive accounting of Shuttle development and procurement costs, based on Shuttle direct obligations as presented in NASA budget estimates, was performed in 1984 by David Stuart, now with TRW Corp. The figure of $15 billion is a rounded estimate that appears in R.H. Miller, D.G. Stuart, and A. Azarbayejani, "Factors Influencing Selection of Space Transportation Options," paper presented at the 37th Congress of the International Astronautical Federation, ref. No. IAF 86-108, Innsbruck, Austria, Oct. 4-11, 1986.

[12] Dr. Robert Barthelemy, briefing on NASP to members of U.S. Senate, Russell Office Building, Apr. 20, 1989.

Box 5-A—NASP, the Orient Express, and High-Speed Commercial Transports

In his January 1986 State of the Union Message, then President Ronald Reagan proclaimed, "We are going forward with research on a new 'Orient Express' that could, by the end of the next decade, take off from Dulles Airport [near Washington, DC] and accelerate up to 25 times the speed of sound, attaining low-Earth orbit, or flying to Tokyo within two hours." The President's speech placed NASP on the national agenda, but it also led to considerable confusion over the objectives of the program. At present, the NASP program has no plan to develop an Orient Express.

The principal objective of the NASP program is to build a Mach 25 experimental vehicle, the X-30, that would develop, and subsequently demonstrate, the technologies for single-stage access to space. In contrast, the Orient Express is a *concept* for a commercial hypersonic passenger transport. In addition, the maximum speed of the Orient Express (roughly Mach 5 to Mach 10) would be far less than the Mach 25 orbital speed required for the X-30.

NASA is studying the feasibility of a commercial supersonic transport in its High-Speed Civil Transport Program (HSCT), an effort distinct from NASP. HSCT design objectives include a range of 7,500 statute miles (6,500 nautical miles) with a full payload of 300 passengers (based on Pacific region markets) and a maximum weight of not more than 1,000,000 pounds to maintain compatibility with existing airports. Environmental compatibility and economic viability are the two most important parameters governing HSCT designs. These factors in turn depend on airport noise, sonic boom[1], effects on atmospheric ozone, aircraft productivity, and operating and production costs.

Initial HSCT studies have shown Mach 6 and above to be commercially noncompetitive with supersonic transports in the Mach 2-3 range as a result of the slowing of aircraft productivity with increasing Mach number and the relatively high cost of using hydrogen fuel to achieve the higher speeds. Mach 2-5 supersonic transports could burn conventional petroleum-based fuels or cryogenic methane.

Some HSCT studies suggest that Mach 3.2, the practical speed limit for a kerosene-burning transport would be the optimum choice in the near-term (year 2000+). Using kerosene eliminates the need for the exotic engines, materials, and cryogenic fuel transfer and storage facilities that are necessary for Mach 5+ flight. Studies also show that a Mach 3.2 vehicle could weigh some 450,000 pounds less than a Mach 5 transport, thus lowering vehicle size, cost, and, indirectly, sonic boom. However, an important factor that could undercut the commercial viability of a Mach 3 transport after the year 2,000 is the anticipated improvement in the next generation of sub-sonic transports.

Although there is some overlap in the technical development necessary to realize these aircraft, a Mach 3 supersonic transport would have essentially no value as a stepping stone to building the X-30, and a Mach 5+ Orient Express would have only a limited value. Conversely, while the development of the X-30 could spur the development of the Orient Express, some X-30 materials, propulsion concepts, cooling techniques, etc. would be either unnecessary or too costly for a commercial transport. The NASP program would not provide a direct route to supersonic commercial transport, nor is it likely to be the most economical route to commercial hypersonic transport.

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[1] Assuming similar wing loading (a function of aircraft weight), the sonic boom of a hypersonic aircraft could be similar to a supersonic aircraft. Hypersonic transports would cruise at higher altitudes where there are large temperature gradients and inversions. Since the speed of sound has a temperature dependence, these temperature variations break up an aircraft's shock wave and reduce its effect on a particular ground location.

payload (some of which would be devoted to "margin" for items such as extra fuel). The required orbital trajectory (polar or low inclination) would also affect vehicle size, weight, and payload-carrying capability. The NASP Joint Program Office (JPO) has studied designs that range in weight from less than 200,000 pounds to over 300,000 pounds.[12]

The objectives of the NASP program as currently structured include the following:

- *Single-Stage-To-Orbit (SSTO):* The foremost objective of the X-30 would be to achieve orbit using a single propulsion stage in a fully reusable flight vehicle. An SSTO vehicle would reach low-Earth orbit without carrying expendable booster rockets or external fuel tanks. In principle, a fully reusable SSTO design may have a greater potential to reduce the cost for a vehicle to reach orbit than a multi-stage air-breathing/rocket combination. However, achieving SSTO with a reusable vehicle is also more challenging technically than alternative methods for reaching orbit such as the two-stage vehicles being studied by NASA (see ch. 4).[13]

  To achieve orbit in a single-stage would require both efficient scramjet performance at high Mach numbers and extremely high propellant fuel fractions. Scramjets must retain their theoretical advantages in performance over conventional rocket engines to high Mach numbers if the X-30 is to achieve SSTO. High propellant fuel fractions can only be accomplished in a design with very low structural weight fractions because the payload is expected to be only a small fraction (on the order of 5 percent) of the vehicle gross weight. Thus, payload could not be reduced to compensate for excessive structural weight. Attaining very low structural weight fractions poses particular challenges in the X-30 because it must contain a large volume of low-density liquid hydrogen (or hydrogen slush) fuel, and its structures must be able to withstand high aerodynamic and aerothermal loads.
- *Air-Breathing Propulsion to Hypersonic Speeds:* The speed necessary to enter low-Earth orbit is approximately Mach 25. As originally conceived, the X-30 would have attempted to reach this speed using only air-breathing propulsion. However, all of the X-30 designs now under consideration by the NASP JPO include options to carry liquid oxygen (LOX) on-board for thrust augmentation. LOX would either be combined with hydrogen in separate reusable rockets, or it could be added directly to the scramjet engines. Some form of rocket assist would also be necessary for propulsion when the vehicle rises above the sensible atmosphere, that is, for final insertion into orbit,[14] maneuvering in space, and de-orbiting.
- *Hypersonic Cruise:* Although the prime focus of the X-30 program is on demonstrating the ability to reach orbit with a single propulsion stage, it would also demonstrate the capability for prolonged flight at hypersonic speeds within the atmosphere.
- *Horizontal Take-Off and Landing From Conventional-Length Runways:* The X-30 is being designed to enable take-off and landing from 10,000-foot-long runways as part of a plan to demonstrate the potential for responsive and economical operations in military and civilian follow-on vehicles.
- *Powered Approach to Landing and Go-Around Capability:* The X-30 and operational follow-ons could use their low-speed propulsion systems to allow a landing under power. At a penalty of carrying an extra several thousand pounds of fuel to orbit, this propulsion capability would allow a launch vehicle returning to Earth to have go-around capability—the ability to abort a landing, circle an airfield, and retry the landing. Go-around is viewed as a desirable, but far from essential, capability in an opera-

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[12] Dr. Robert Barthelemy, briefing on NASP to members of U.S. Senate, Russell Office Building, Apr. 20, 1989.

[13] There are a number of complex tradeoffs that would have to be evaluated to determine whether SSTO vehicles would, in fact, be more cost effective than TSTO (two-stage-to-orbit) vehicles. TSTO vehicles could use lower-risk technology than SSTO vehicles and they could have larger performance "margins." On the other hand, TSTO vehicles could require more complicated and expensive ground operations. Safety would be of paramount importance for a launch vehicle that would be used to transport humans. Therefore, the costs to certify a launch vehicle as flight ready would also have an important effect in determining which design would be most cost effective.

[14] The X-30 would follow a steep trajectory during its final ascent to orbit. A small amount of rocket power is necessary to circularize the final orbit and to place the vehicle at the desired altitude.

tional vehicle. It could be traded for larger payloads or used as ''margin'' against performance shortfalls. In that case the vehicle would make a gliding re-entry like the Shuttle.

- *''Aircraft-like'' Operability:* The X-30 would attempt to demonstrate the potential for operating future hypersonic cruise and launch vehicles in a manner that more closely resembles today's airline industry than the civilian space program. This may be the most challenging objective of the NASP program, for although the X-30 may resemble an aircraft, it would be a radical departure from all previous aircraft designs.

  In particular, the X-30 would attempt to demonstrate the potential for service and maintenance turn-around times of 1 day or less, safety and reliability factors similar to those of aircraft, 150 flights without major refurbishing, and the elimination of the complex launch and support facilities and large ''standing army'' of technicians that have typified rocket launches. According to the NASP JPO, rapid turn-around is essential for many military applications and it is the key factor in reducing operation and support costs.

Flight tests of two X-30s would be conducted from Edwards AFB, California over a 2-year test program scheduled to begin in October 1994. The flight control system, the pilot-instrumentation interface, crew escape systems, and solutions to the potential for communication disturbances or blackout (by air heated so hot it forms a plasma around the vehicle) would all be tested in this period. The flight control system for a hypersonic vehicle poses particular challenges, in part because of the coupling between the propulsion system and the vehicle's aerodynamics.

FUNDING AND SCHEDULE

NASP grew out of a $5.5 million 1984 Defense Advanced Research Project Agency (DARPA) study called ''Copper Canyon'' that revived interest in the potential for hypersonic propulsion (see box 5-B). At the time of the Copper Canyon study, some 300 people were engaged in research in what is now called NASP. Today that number has risen to over 5,000.[15]

Federal funding for NASP has come mostly from the Department of Defense (Air Force, Navy, Strategic Defense Initiative Organization, DARPA) with smaller contributions from NASA. Beginning in fiscal year 1988, all DoD funding was consolidated within the Air Force.[16] The Air Force and NASA are managing NASP in a Joint Program Office at Wright-Patterson Air Force Base, Ohio. Industry is also making a major contribution to NASP funding.[17] Total industry contributions to the program, now over $500 million, could amount to $700 million by September 1990. Most funding is occurring in the current technology maturation and concept validation phase of the progam. Some of these investments include items of major capital investment such as wind tunnels, supercomputers, and materials research facilities that have applications in projects other than NASP. Figure 5-3 shows the NASP schedule currently envisioned by the NASP Joint Program Office.

Table 5-1 gives a breakdown of NASP's funding by NASA and the Department of Defense. Congressional concern that NASA's civilian role in the program was too limited was expressed in the DoD Appropriations Act for fiscal year 1987 and is reflected in subsequent budgets.[18]

The NASP program would undergo dramatic change if the revised budget proposals submitted by Secretary of Defense Cheney, in April 1989, were

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[15] Dr. Robert Barthelemy, NASP Program Director, at OTA briefing, Dec. 13, 1988.

[16] See General Accounting Office *National Aero-Space Plane*, p. 19.

[17] Contractors have expressed concern about the burden being imposed on them as a condition to participate in NASP. Dr. Joseph F. Shea, chairman of the 1987-88 Defense Science Board (DSB) study of NASP concurred in this concern, stating in a letter that accompanied the transmission of the DSB report, ''I am compelled to point out that the concept of heavy cost sharing by the contractors is not realistic. The near-term business potential to be derived is not large enough. . .'' Major industrial funding is scheduled to cease after NASP completes the ongoing demonstration, validation, and design activities, and, if approved, enters Phase III development.

[18] See GAO *National Aero-Space Plane*, p.29.

Box 5-B—The Origins of NASP[1]

Supersonic flight first occurred in 1947 when Chuck Yeager, flying the Bell X-1 to a speed of 700 mph, became the first person to break the sound barrier. The U.S. "X" plane (experimental research aircraft) program to develop supersonic and hypersonic aircraft continued throughout the 1950s and 1960s, culminating in the creation of the X-15, a rocket powered aircraft that set speed and altitude records of Mach 6.7 and 354,200 feet, respectively, before the program was canceled in 1968. The X-15 was essentially a flying fuel tank that could literally fly to the edge of space, although it lacked the propulsive capabilities to achieve orbit. The program was cancelled in 1968.

The X-20 "Dyna-Soar" program contributed substantially to the technical database on hypersonic flight, even though a flight vehicle was never built. Before the X-20 program, hypersonic data had been derived primarily from ballistic missile programs using blunt, nonlifting entry bodies. The X-20 was intended to be a piloted space glider that would have been launched by a Titan III missile and its design would have allowed it to glide horizontally within the atmosphere, and land horizontally on a runway. Among its proposed missions were reconnaissance and satellite inspection.

The X-20 was a costly program and some Administration officials, including Secretary of Defense McNamara, questioned the necessity for a spaceplane to perform the missions proposed for the X-20. McNamara canceled Dyna-Soar in December 1963, citing the possibility of using a manned orbiting space laboratory for some of the X-20 missions and noting that several hundred million dollars would be necessary to finish the program. At the time of the cancellation government expenditures for the X-20 totaled over $400 million (roughly $1.5 billion in current dollars).

Research on hypersonic vehicles and propulsion systems continued throughout the 1960s and 1970s, but was given a relatively low priority. For example, a late 1970s cooperative effort between NASA and the Air Force to develop a National Hypersonic Flight Research Facility never matured beyond the planning stage. Nevertheless, research into hypersonic technologies never ceased. Research into advanced propulsion concepts led to the fabrication of scramjet components that were tested in wind tunnels at speeds up to Mach 7.

Continued on next page

adopted by Congress.[19] Under the revised DoD budget, overall control of the program would be transferred to NASA, and support in fiscal year 1990 would be cut by 66 percent to $100 million. DoD funding of NASP in subsequent years would cease. NASA's contribution to NASP would also likely be revised if the DoD revisions were enacted. The potential effect of large revisions in the NASP budget is discussed later in this report. In the following discussion of the NASP schedule it is assumed that control of the program is retained within DoD and funding remains close to President Reagan's budget submission of February 9, 1989.

The Copper Canyon study, in effect, was Phase I, "concept feasibility," of NASP. Phase II, "concept validation," began in 1985 and is now scheduled to be completed in late 1990. A major part of Phase II is the "Technology Maturation Program," an effort to develop the requisite technologies and fabrication techniques for the X-30. Currently, the prime NASP contractors are Rockwell, General Dynamics, and McDonnell Douglas (airframe); and Rocketdyne and Pratt & Whitney (engines). The airframe companies are responsible for the design of the overall system, including the airframe itself, the cryogenic fuel tank, and structures such as leading edges and nose tip.

Out of hundreds of initial airframe/engine configurations, six are presently under consideration (all three airframe contractors have presented plans that use either of the two engine designs). The five contractors are scheduled to be combined into a

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[19] The revised budget was submitted by the Secretary of Defense as part of a bipartisan budget agreement between President Bush and congressional leaders that cut some $10 billion of budget authority from President Reagan's fiscal year 1990 DoD budget of $305.6 billion. (Molly Moore, "Pentagon May Lose Weapons," *The Washington Post*, Apr. 15, 1989, p.1)

The direct origins of NASP can be traced to Air Force support in the late 1970s and early 19802 for what became known as the transatmospheric vehicle (TAV) concept. TAV may be viewed as a legacy of Dyna-Soar. It was seen by the Air Force as a potential cargo-carrying successor to the Shuttle to carry defense payloads to orbit, and as a military vehicle with the potential for global response. The Air Force studied many configurations of TAV, but in contrast to the current NASP program, most envisioned a vehicle that would incorporate *rocket* propulsion, such as advanced versions of the Space Shuttle's main engines.

By 1984, TAV had grown into a major Air Force study effort. Support for TAV at the Air Force Space Command came from its potential contribution to four key military space missions: Force Enhancement (including global reconnaissance; surveillance; and command, control, and communications) Space Support (including satellite insertion, rendezvous, inspection, servicing, repair, recovery, and support of Space Station) Space Control (including protection of U.S. space assets) and Force Application.[2] Support for TAV was also spurred by the Strategic Defense Initiative, announced in March 1983, and by President Reagan's commitment to NASA to build a space station.

In early 1984, DARPA undertook a study to evaluate the possiblilites for hypersonic, air-breathing propulsion. DARPA's "Copper Canyon" study grew to embrace TAV concepts becoming, in effect, a TAV with air-breathing propulsion. By the end of 1985, the Air Force, DARPA, NASA, SDIO, and the Navy were all studying concepts for a TAV/Advanced Aerospace Vehicle (AAV), including single-stage-to-orbit concepts. NASP replaced the TAV/AAV designation as of December 1, 1985. It became a national program following President Reagan's 1986 State of the Union Address. Overall control of the program was transferred from DARPA to the Air Force in 1988.

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[1] The history of hypersonic flight and the origins of NASP are discussed in a remarkably rich and detailed history edited by Air Force historian Richard P. Hallion, *The Hypersonic Revolution: Eight Case Studies in the History of Hypersonic Technology, vol I, 1924-1967, From Max Valier to Project Prime, vol II 1964-1986, From Scramjet to the National Aerospace Plane*, (Special Staff Office Aeronautical Systems Division, Wright-Patterson Air Force Base: Dayton, OH 1987). Note: Distribution limited to DoD and DoD contractors. See also Scott Pace, *National Aerospace Plane Program: Principal Assumptions, Findings, and Policy Goals*, Rand Publication P-7288-RGS (Santa Monica, CA.: The RAND Corp., 1986), T.A. Heppenheimer, "Can Hard Science Save The Aerospace Plane?" *The Scientist*, vol. 2, No. 19, Oct. 17, 1988, pp. 1-3, and John D. Moteff, *The National Aerospace Plane: A Brief History*, Congressional Research Report for Congress # 88-146 SPR (Washington DC: Feb. 17, 1988).

[2] Hallion, *The Hypersonic Revolution*, Ibid., pp. 1341-42.

single national team by 1990. The five engine and airframe contractors have also been combined in a novel cooperative materials consortium that began in March 1988 and is budgeted at $150 million for a 30-month period (see app. D).

NASP's current schedule (see figure 5-3) calls for a decision to be made in September 1990 on the feasibility of proceeding with Phase III of the program, which would include advanced design, fabrication, and flight tests of two X-30s. Portions of a third vehicle would also be built for tests on the ground. In addition to building the X-30s, Phase III would also continue NASP's Technology Maturation Program. If the program is able to keep its current schedule, a 2-year flight test program would begin in October 1994. During the test program the X-30 could undergo some modification. A potentially more expensive option would be to build the two X-30 vehicles sequentially and incorporate changes in the second vehicle based on flight data from the first. *Assuming no delays*, officials believe the SSTO objective could be achieved by September 1996.

NASP officials project total costs through fiscal year 1996 to be roughly $3.9 billion. Peak funding levels are expected between fiscal year 1992 and fiscal year 1994, when an estimated $550 million will be requested annually to build the two X-30 vehicles.[20] NASP funding estimates are highly uncertain because some of the full-scale materials production techniques have not been completely developed, manufacturing and fabrication techniques are new, and designers have little or no experience with estimating costs for building a hypersonic vehicle. Furthermore, Phase III budgets are based on an extrapolation from an early DARPA

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[20] Statement by NASP program head Dr. Robert Barthelemy reported in *Aerospace Daily*, vol. 147, No. 58, Sept. 22, 1988, p. 457.

Photo credit: General Dynamics Corp.

One conceptual design for the X-30 National Aero-Space Plane.

Copper Canyon design for an X-30 whose empty weight was only 50,000 pounds.[21] Vehicle weights have increased since then as designers have acquired more test data and adopted more conservative designs.

Designers believe that the empty weight of the X-30 will be the key factor in determining procurement costs. This is because the structural weight of an aircraft influences propulsion requirements and material costs directly, and because it indirectly affects the size and cost of many other aircraft components. The JPO has established a cost estimation group for the X-30 in preparation for its Phase III review.

In an admittedly highly optimistic scenario, NASP officials told OTA that if the NASP program were to make very rapid progress, a concurrent program to build an operational vehicle could commence while the X-30 was being flight-tested in Phase III. An ambitious schedule projects that an operational vehicle program could be completed before the year 2000. Achieving this goal presumes a completely successful X-30 flight test program without long delays from unexpected technical problems, budgetary restrictions, or cost growth in the program. It also presumes rapid progress in translating X-30 technology into an operational vehicle. Finally, it presupposes that an operational vehicle would bear close similarity to the X-30 in order to minimize new development efforts and flight-testing.

A more conservative approach would wait for the completion of Phase III before starting an operational program. If such a program began in the late 1990s, a first-generation operational vehicle would not be expected until approximately the year 2005, assuming the development cycle of the X-30 follows previous development cycles for fighter aircraft derived from experimental vehicles.[22] Second-generation operational vehicles, which might possess increased performance, bear larger (Shuttle-class) payloads, or have better safety and operability than first-generation X-30 derivatives, would require a longer development cycle. Assuming first-generation follow-ons are available in 2005, a very rough estimate for the date of Initial Operational Capability (IOC) of these vehicles might be 2010 or later.

NASP TECHNOLOGIES

There is an inherent risk in building a vehicle that departs radically from all its predecessors and whose design cannot be fully validated before flight testing. Further complicating already challenging engineering problems are the complex interrelationships between technologies caused by the necessity to design the X-30 as an integrated package. The following is a brief review of some of the challenges

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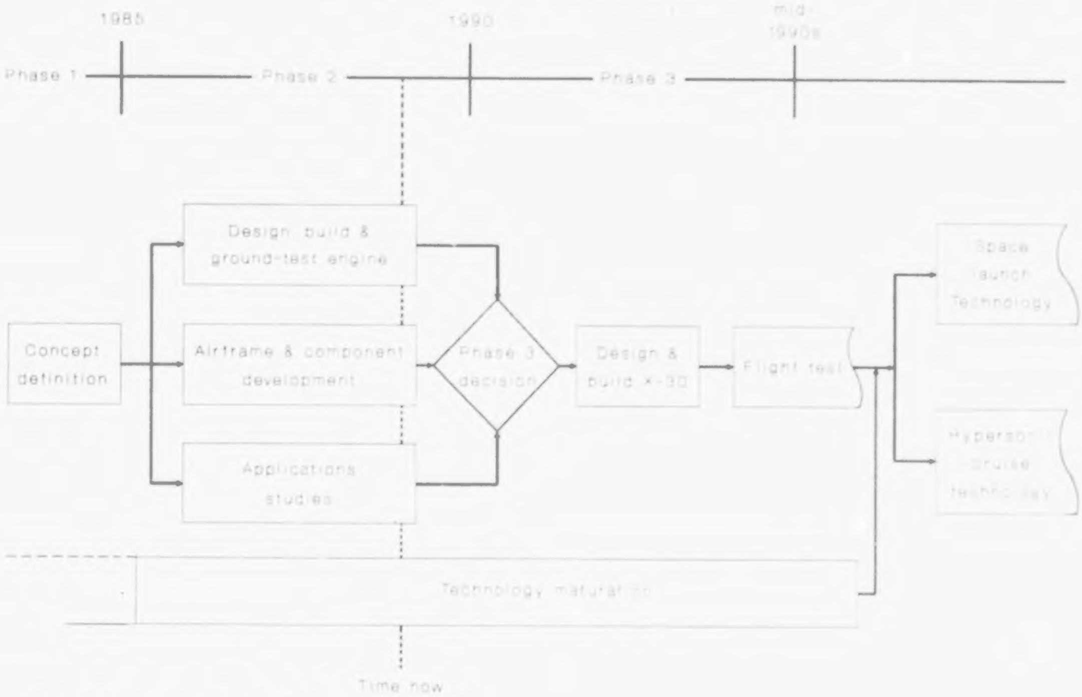
[21] "Phase III Alternatives: Contractor Findings," in *National Aero-Space Plane Program Briefing to NASP Steering Committee*, Nov. 7, 1988, p. 49. Contractor concerns that Phase III costs could exceed preliminary Phase III budgets was also expressed.

[22] Scott Pace, "National Aerospace Plane Program: Principal Assumptions, Findings, and Policy Options," Publication # P-7288-RGS, The Rand Graduate School Santa Monica, CA, pp. 10-11. NASP officials point to the rapid development cycle of the SR-71 to support their contention that an operational vehicle could be built sooner than 2005. They also note that in some respects the propulsion and materials challenges that faced the SR-71 are analogous to those facing the X-30 and an NDV. However, the SR-71 suffered several years of troubled operation after the delivery of the first production units. The SR-71 example holds lessons for both proponents and critics of accelerated development.

Figure 5-3—NASP Program Schedule



SOURCE: National Aero-Space Plane Office.

Table 5-1—NASP Funding (in millions of dollars)

	FY 86	FY 87		FY 88		FY 89		FY 90		FY 91	
								(PB)[a]	(RB)[b]	(PB)	(RB)
DoD	45	110	(149)[c]	183	(236)	228	(245)	300	100	390	0
NASA	16	62	(62)	71	(84)	88	(104)	127	127[d]	119	?
Total	61	172	(211)	254	(320)	316	(349)	427	227	509	?

[a] President Reagan's budget submission—February 1989.

[b] DoD revised budget—April 1989.

[c] Numbers in parenthesis represent budget requests from previous fiscal years.

[d] NASA outlays are expected to be reduced if the revised DoD budget is approved.

SOURCES: **For FY 1986-88:** "National Aero-Space Plane Program Briefing to NASP Steering Committee," (NASP Joint Program Office, Nov. 7, 1988), p. 21
For FY 1989-91: NASP JPO and Rockwell Corporation.

to be met in developing the key enabling technologies of the X-30.[23]

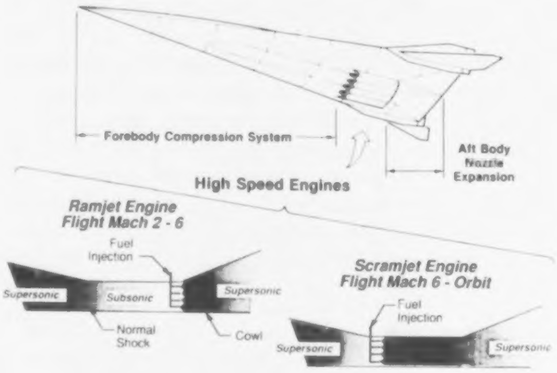
Propulsion

The X-30 would differ from all previous aircraft in its use of air-breathing engines instead of rockets to reach hypersonic speeds. One measure of fuel efficiency is the specific impulse, I_{sp}, which is defined as the thrust delivered per unit mass of propellant burning in one second.[24] By avoiding the necessity to carry an oxidizer, air-breathing engines can achieve higher specific impulses than rockets, although their advantage diminishes with increasing speeds (figure 5-4). The higher I_{sp} of air-breathing engines makes a single-stage-to-orbit vehicle a possibility despite the necessity to carry the weight of wings and landing gear to orbit.

Jet engines generate thrust by admitting air through an inlet, compressing a mixture of fuel and air in a combustion chamber (combustor), igniting the mixture, and letting the hot, compressed exhaust products expand through a nozzle opening at high speed. Compressing the fuel-air mixture before it is ignited raises the temperature and pressure of the mixture; this facilitates combustion and improves the overall fuel efficiency of the engine.

Different configurations of air-breathing engines would be needed to operate at subsonic, supersonic, and hypersonic speeds within the atmosphere (see app. C). Scramjets could, in principle, power an aerospace plane from about Mach 5-6 to orbital speeds (about Mach 25), assuming that theoretical predictions of scramjet performance at high Mach numbers prove accurate, and assuming that the fraction of the spaceplane's weight that was devoted to structures could be made extremely small (the precise number is the subject of some debate). All designs face the challenge of producing a propulsion package that meets stringent aerodynamic and weight constraints.

Figure 5-4—High-Speed Propulsion System



SOURCE: Adapted from NASP Joint Program Office.

The X-30 would be the first vehicle to reach hypersonic speeds propelled by scramjets. All designs envision the placement of a series of scramjet modules side-to-side across the bottom of the aft section of the vehicle (figure 5-5). In this way the long forebody of the aircraft effectively becomes part of the engine inlet, and with careful design it will capture much of the air moving past the vehicle and channel it into the engine inlets. The required air compression in the combustor would be provided by coupling the underside bow shock through the engine inlets. The three airframe contractors have proposed different configurations for the X-30. With

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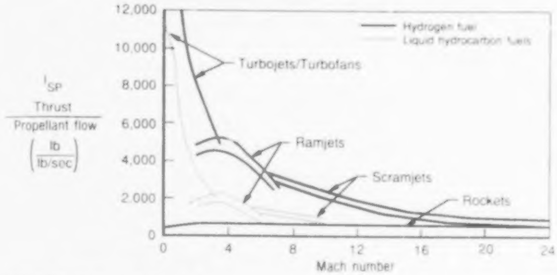
[23] The discussion here and in the appendices is meant to serve as a brief tutorial. More thorough, and technically more sophisticated reviews, are *Report of the Defense Science Board Task Force on the National Aerospace Plane (NASP)* (Washington DC: Office of the Under Secretary of Defense for Acquisition, 1988); and *Hypersonic Technology For Military Application*, op. cit., footnote 4. NASP's key technical challenges are also reviewed in the GAO report *National Aero-Space Plane*, op. cit., footnote 4. Excellent popular introductions to NASP technologies are found in: T.A. Heppenheimer, "Launching the Aerospace Plane," *High Technology*, July 1986, pp. 46-51; and John Voelcker, "The iffy 'Orient Express'," *IEEE Spectrum*, August 1988, pp. 31-33.

[24] Thrust, or force, is usually expressed in units of pounds, and propellant mass flow rate is commonly expressed in "pounds" per second. Thus, I_{SP} is usually expressed in "seconds." Strictly speaking, the propellant mass flow rate should be measured in units of mass per second, not weight per second. In that case, I_{SP} would have units of velocity.

Figure 5-5—Engine I_{sp}



SOURCE: McDonnell Douglas.

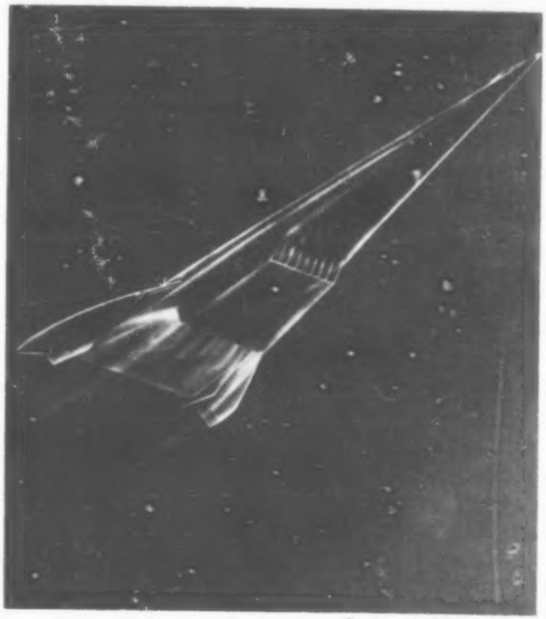


Photo credit: Rocketdyne Corp.

Conceptual airframe and engine design for the X-30 National Aero-Space Plane.

respect to the vehicle forebody, their designs reflect compromises among aerodynamic drag, inlet compression efficiency, and structural considerations. NASP officials have not yet chosen a final design.

All designs also envision making the airframe afterbody part of the engine, in effect serving as a nozzle and surface to expand the exhaust products. This eliminates the weight of a nozzle and can also help reduce the drag that results from the pressure differential that develops between the front and rear surfaces of the aircraft. The amount of forward thrust generated by the scramjets is a sensitive function of the intake airflow and the resultant exhaust expansion. Similarly, vehicle drag at high speeds is a sensitive function of engine geometry. Again, this illustrates the necessity to optimize performance by designing airframe and engine together.

To reach orbit, the X-30 would rely on efficient performance of scramjets at speeds in excess of those that can be fully tested in ground facilities. In addition, although scramjets can in principle produce positive thrust all the way to orbital speeds, their propulsion efficiency as measured by engine specific impulse declines as vehicle speed increases (see figure 5-5). A plot similar to figure 5-5 that included the effect of drag on the vehicle (effective I_{sp}) would show that as vehicle speed increases, the net thrust decreases. Thus, a scramjet-driven hypersonic aircraft will be operating with very little tolerance for unexpected thrust losses, or increases in drag at the higher Mach numbers.[25] The importance of this sensitivity could be lessened, at some penalty in performance, by augmenting scramjet propulsion with auxiliary rocket power. In addition, the high-speed thrust sensitivity of a vehicle would vary greatly with specific engine and airframe designs.

As part of a risk reduction plan, propulsion systems under consideration by the NASP JPO have an option to augment the thrust of scramjet engines with an auxiliary rocket-based propulsion system before the vehicle reaches orbital speeds. In these designs, liquid oxygen is carried on-board the X-30 and either added directly to the scramjet engines or combined with hydrogen to power a separate rocket propulsion system. Either approach involves design tradeoffs. If separate rockets were chosen for thrust augmentation they would be resuable and relatively small, equivalent to the class of rockets needed to propel an orbital transfer vehicle from low-Earth orbit to geosynchronous orbit.

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[25] Stephen Korthals-Altes, "The Aerospace Plane: Technological Feasibility and Policy Implications" (S.M. thesis, Massachusetts Institute of Technology, Cambridge, MA: 1986), pp. 50-55. The thrust sensitivity issue is also discussed in Bill Sweetman, "Scramjet: The NASP propulsion goal," *Interavia*, November 1987, p. 1208.

The speed at which auxiliary power might be used during ascent is a complicated issue dependent on many design factors. The disadvantages of early rocket turn-on, or LOX augmentation of air-breathing engines, includes the need to carry heavy liquid oxygen and tankage on-board. The resulting heavier take-off weight of the vehicle increases the required wing area, take-off speed, and overall size and cost of the vehicle. On the other hand, additional liquid oxygen is 50 percent more dense than jet fuel and thus takes up relatively little space. Hydrogen tankage is necessarily large because of the low density of liquid hydrogen, roughly one tenth of jet fuel. In fact, this is one of the reasons slush hydrogen is being considered as a fuel (see *Fuel* discussion below). Furthermore, at the very high speeds where auxiliary power would be used, scramjets would be operating in a mode that consumes extra amounts of hydrogen.[26]

Several other factors would affect the choice of rocket transition point, including:

- the X-30 will be subjected to higher drag while in the atmosphere, but the drag would drop substantially if the vehicle entered a low-drag rocket trajectory;
- the specific impulse of scramjet engines is expected to drop off rapidly at higher Mach numbers; and
- scramjets tend to have less thrust available at higher Mach numbers where rockets have no such limitation.

According to NASP airframe contractors, the X-30 could achieve SSTO even carrying the extra weight associated with an auxiliary propulsion system. However, SSTO performance could be attained only if scramjets perform close to theoretical expectations, and only if extremely low structural weight fractions were achieved. A disputed point among some propulsion and materials/structures experts is whether near-term technology is sufficiently mature to meet both these requirements. The program management implications of this issue are discussed in the *Policy and Options* section of this chapter.

Fuel

Ordinary hydrocarbon fuels like kerosene, or the more specialized derivatives used on some high-performance aircraft, would not be suitable for the X-30's scramjets. The amount of thrust that could be derived from the combustion of these fuels is too low compared with their weight, and they could not be mixed or burned efficiently in the hypersonic airflow of an X-30-sized combustor. As the X-30 accelerates towards Mach 25, air will sweep fuel through the combustion chamber in times on the order of 1 millisecond. Sustaining combustion and avoiding flameout in these fast flow situations presents complex problems.

One part of the solution to these problems will be the use of hydrogen as fuel. Hydrogen has the highest energy content per unit of mass of any fuel. It also provides a burning velocity improvement of a factor of five relative to conventional hydrocarbon-fuels, and should allow the burning process to be completed without unreasonably long combustion chambers.[27] By itself, however, hydrogen would not solve all of the problems of igniting and burning fuel traveling at hypersonic speeds. For example, engine designers must also incorporate special "flameholding" techniques to stabilize the flame in scramjet combustors without compromising engine aerodynamics or adversely affecting combustor conditions.

Hydrogen fuel offers several other advantages over conventional fuels:

- The large heat capacity of hydrogen provides a possible heat sink for the enormous thermal loads to which the X-30 would be exposed;
- Its exhaust products are predominantly water vapor, which is expected to prove environmen-

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[26] At very high speeds a significant fraction of the scramjet's thrust would be derived from hydrogen that was added to the combustor, but did not undergo a chemical reaction with oxygen. As hot hydrogen is expanded from the higher pressure combustor to the lower pressure nozzle, it cools, converting heat into kinetic energy and adding to the thrust.

[27] However, according to the Air Force Studies Board Report on Hypersonic Technology, the reaction between hydrogen and oxygen in the combustor would not be complete before the mixture reached the engine nozzle. Unless the reaction was substantially completed during the expansion process some of the energy available from the propellant would not be used to produce thrust.

tally safe when produced at the very high altitude flight paths of hypersonic vehicles[28];

- It does not produce noxious fumes, and there is less danger from spreading flame than there would be from conventional fuels because it is less dense than air; and
- It could be combined with oxygen in a fuel cell to generate electrical power for the X-30.

Hydrogen gas would be derived from tanks of liquid hydrogen in order to permit enough fuel to be stored in a reasonably sized container. However, despite its higher energy content, liquid hydrogen's low density will result in fuel tanks some five times larger than equivalent hydrocarbon fuel tanks.[29] As a result, NASP engineers are exploring the feasibility of using slush hydrogen—a mixture of 50 percent solid and 50 percent liquid hydrogen that is roughly 15 percent more dense than liquid hydrogen. The slush would have a greater density and greater cooling power than liquid alone. The other major concern with hydrogen is the potential problem of hydrogen embrittlement in materials (see below).

Hydrogen would also be circulated through the engine, and in some designs through the airframe, as a coolant and as a means to increase combustion efficiency. Regenerative cooling is a technique typically employed by designers of liquid rocket engines to recover waste heat. By cooling the engine with fuel, the energy of the propellant is increased before it is injected into the combustion chamber. The addition of thermal energy to the propellant results in an increase in the velocity of the exhaust gases. If the exhaust nozzle is designed properly, the extra energy of the expanding gases will produce more thrust. The use of regenerative cooling techniques in the X-30 would allow waste engine heat, or heat generated by aerodynamic heating (friction), to be recovered and used to increase engine specific impulse. The recovery of fuel energy would be especially important for hypersonic cruise vehicles.

Materials and Thermal Management

Success in the materials and structures program will have a pivotal effect on the pace at which the X-30 can be developed, the X-30's ability to achieve its design goals, and the extent to which the promised economies of future operational vehicles may be realized (app. D). The projected structural designs for all areas of the vehicle call for high-stiffness, thin-gauge product forms that can be fabricated into efficient load-bearing components. These in turn require high-strength, low-density materials that can retain their characteristics beyond those tolerated by present-day, commercially available materials.

Current challenges center around scaling up laboratory production processes of advanced materials; developing fabrication and joining techniques to form lightweight sandwich and honeycomb structures; and forming materials and coatings that can withstand thermal cycling of the sort that would be seen in a flight vehicle. The potential for material failure under thermal cycling is a particular concern for the X-30 and its possible derivatives because vehicle structures will be exceptionally light, and therefore thin, and temperature differences between inner and outer layers of airframe and engine structures will be unusually large.[30]

Even if their weight could be tolerated, most metals lose their structural integrity above about 1,800 °F. Without cooling, leading edges of the wings, tail, engine, and nose cap of the X-30 could reach temperatures above 4,000 °F. Shock-heated portions of the vehicle could reach temperatures in excess of 5,000 °F, and large areas of the aircraft could be heated to temperatures above 2,500 °F.[31] The greatest stress is within the engine where materials are subjected to the largest simultaneous aerodynamic and aerothermal load.

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[28] The impact of hypersonic vehicles on the ozone layer is the largest concern. The NASP JPO has let contracts for preliminary environmental assessments to evaluate the potential effects of water emissions from X-30 follow-on vehicles, and to evaluate the impact of secondary chemical reactions. Note that the ascending flight profile of a orbital vehicle takes it quickly through the stratospheric band where ozone is concentrated (60,000-75,000 feet).

[29] Stephen Korthals-Altes, "The Aerospace Plane: Technological Feasibility and Policy Implications," p.43.

[30] Consider a thin airframe panel or portion of an engine wall that develops a large temperature gradient during flight because one side is exposed to higher heat or cold. Every time the vehicle is flown, the material would flex slightly because of differential expansion. Under repeated thermal cycles, the continual flexing could eventually lead to permanent deformation or even fracture. Notice that it is the peak, or transient, thermal gradients that govern the scale of this problem. The effects are most worrisome on thin gauge materials since they would fail before thicker materials. The plan to use thin gauge, relatively brittle composite materials for portions of the X-30, and their potential to be exposed to large thermal gradients, is the source of some concern among materials researchers.

The Space Shuttle uses thermal protection tiles to insulate the interior of the vehicle from the high temperatures encountered on reentry. Covering most of the X-30 with thermal tiles would increase vehicle weight and, in addition, would defeat regenerative cooling schemes to increase fuel efficiency unless the tiles could be actively cooled. Instead, the X-30 will cool the hottest airframe structures by circulating hydrogen gas or by employing specially designed "heat pipes."[32]

Using hydrogen cooling raises the potential for hydrogen embrittlement.[33] As hydrogen fuel is transported to the engine it will turn from a liquid to a hot gas, which can diffuse into most materials without difficulty and can form brittle compounds within those materials. The NASP JPO considers the development of hydrogen barrier coatings a critical challenge. The X-30 will require coatings that are thin, lightweight, resistant to damage, and can be applied to complex shapes, including internal passages. Embrittlement could make materials prone to cracking and, in addition, it could affect operations costs and turn-around times if increased maintenance and inspection are required. It could also shorten the useful life of a structural component.

The materials problem is especially difficult in structures that are exposed to both large thermal and mechanical stresses. Perhaps the outstanding example of such a structure is the scramjet fuel injector. To facilitate mixing of hydrogen fuel with air it is necessary to place fuel injectors directly within the very hot engine combustor instead of along the cooler combustor walls. The injectors will experience large mechanical forces. In addition, to keep temperatures from rising beyond material limits, relatively cold hydrogen must be circulated at high pressure within the injector. Even small changes in injector placement and shape could have large effects on the resultant airflow and engine performance.[34]

Computational Fluid Dynamics (CFD) and X-30 Design

The design of the X-30 will require unparalleled use of computer simulation to model the vehicle's aerodynamic behavior at high Mach numbers. Wind tunnels can provide only limited data, as existing facilities can replicate flight conditions only to about Mach 8. Computer modeling performed on the fastest supercomputers is playing a key role in designing and optimizing the X-30's airframe and propulsion system, and predicting the thermal loads that would be encountered by the vehicle.

Computational fluid dynamics (CFD) simulates the behavior of fluids (both gases and liquids) by solving numerically the fundamental equations of fluid motion on a high-speed digital computer. The process of simulating the airflow around an aircraft begins by mathematically generating a picture of the vehicle. Mathematical algorithms calculate airflows over the simulated body at a number of points that are spread out on a mathematical grid. Finer grids and more sophisticated algorithms simulate the resultant airflows with greater fidelity at the cost of increased demands on computer memory and speed. Furthermore, calculations must extend beyond the surface of the vehicle's body to account for important aerodynamic effects, and they must also include flows through engines to evaluate propulsion performance. The critical areas where CFD is being used on the X-30's design are the calculation of airflows around the forebody and engine inlets; inside the engine's combustion chamber (the most difficult set of calculations); around the afterbody and nozzle area; and around the entire integrated engine/airframe.[35]

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[31] X-30 temperatures from, "National Aero-Space Plane," briefing booklet supplied by Director of NASP Program Development, McDonnell Douglas, St. Louis, MO.

[32] A heat pipe is a closed system whose working principles resemble that of an ordinary refrigerator. Heat applied to one end of a heat pipe vaporizes a fluid and causes it to travel to the other end which, for example, might be in thermal contact with a large structure that serves as a heat sink. At the cooler end, the fluid condenses giving up its latent heat of vaporization. The fluid then circulates back to the hotter end of the pipe by capilliary action along a wick. In the X-30, the working fluid could be lithium.

[33] Terrence M.F. Ronald, "Materials Challenges For The National Aero-Space Plane," *Review of Progress in Quantitative Non-Destructive Evaluation* (New York, NY: Plenum Press), May 1989, p.13.

[34] S. A. Dixon et al., "Structures and Materials Technology Issues for Reusable Launch Vehicles," NASA Technical Memorandum 87626 (Hampton, VA: NASA LRC, October 1985), p.15, cited in Richard Hallion, *The Hypersonic Revolution*, vol. II, p.1357.

The end result of a CFD simulation of X-30 flight might be a set of pressure contours or temperature profiles around the vehicle. Such a calculation might take many hours or even days depending on the level of approximation, even when performed on the fastest supercomputers using state-of-the-art algorithms. Moreover, these calculations may be limited in their ability to model turbulent airflows (see box 5-C) a critical issue in NASP airframe and propulsion design.

Because turbulence is characterized by extremely small and rapidly changing eddies, a very detailed simulation would be needed to model turbulence faithfully over large volumes or long time spans. CFD simulations typically include turbulent flow only in a semi-empirical way, adding its effects to theoretical models of smooth flow by the ad hoc inclusion of terms based on experimental data. While the resultant models may be valid over some narrow range of conditions, their application at the extreme conditions that would be encountered in reaching orbit introduces uncertainties. Validating CFD models is thus a critical issue for NASP. Unfortunately, no existing or planned ground test facility could simulate *simultaneously* the equivalent temperatures, pressures, air speeds, and turbulent effects that a spaceplane would encounter in its ascent to orbit.

Wind tunnels, the primary means to acquire experimental data, cannot produce long-duration air flows with true temperature simulation over Mach 8 in volumes large enough to hold full-size engine and airframe structures. For example, "blowdown" facilities produce gas flows above Mach 8 by gas expansion, but the process also results in very low gas temperatures. However, because the Mach number in the combustor is roughly one-third of free stream,[36] even Mach 8 wind tunnel facilities can provide some engine aerodynamics data over most of the X-30's speed range. Still, its quality decreases at higher Mach numbers. Other challenges for wind tunnels include simulation of "real gas" effects—effects that are the result of the formation of chemically reactive and excited-state atomic and molecular species as a vehicle moves through the upper atmosphere at hypersonic speeds. It is particularly important to develop models that include real gas effects when describing conditions within the X-30's engine.

Pulse facilities ("shock tunnels") can simulate the heat content and pressure of air at speeds as high as Mach 20, but the short duration of their flows (typically 10 milliseconds or less) prevents full steady-state conditions from being achieved and makes instrumentation difficult. Moreover, the size of test models is usually restricted in shock experiments. NASP is funding refurbishment and upgrading of several pulse facilities. A new Rocketdyne test facility that may open in 1990 promises to allow full-scale engine component testing up to Mach 24.[37]

Hypersonic data gathered by the Space Shuttle would be of limited use in designing the X-30 because the Shuttle's shape and trajectory differ too much from prospective NASP vehicles and flight paths (the data would be of some use in validating numerical simulation models of hypersonic flight). Currently, NASP has no plans to gather hypersonic data experimentally by deploying test vehicles from the Shuttle, dropping projectiles from high-altitude balloons, or by using ground or aircraft-carried rockets. The position of the JPO is that such a program would be a significant experimental undertaking that would consume large amounts of time

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[35] In a recent report, the chief scientist at the Air Force's Arnold Engineering Development Center stated that it took a year to set up the grid and solve the flow field for the F-16 fighter. Another project to model the F-15 fighter took four engineers working part-time six months. However, automated processes are reducing the time to set up vehicle grids. NASP officials predicted that it will soon be possible to make changes in airframe configurations and re-grid the model in times on the order of 6 weeks. John Rhea, "The Electronic Wind Tunnel," Air Force Magazine, vol. 72, No. 2, February 1989, pp. 62-66. This article gives an overview of CFD efforts at Arnold Engineering Development Center and other Air Force laboratories.

[36] The fluid Mach number is inversely proportional to the ratio of the square root of the temperature of the gas in the combustor divided by the temperature of the gas in the free stream (the temperature of the gas far out in front of the vehicle).

[37] William B. Scott, "Rocketdyne Developing Facility for Hypersonic Propulsion Tests," *Aviation Week and Space Technology*, Jan. 30, 1989, p. 65. This facility will be a reflected shock tunnel and should be able to simulate some of the temperature, pressure, and real gas effects that would be encountered by the X-30 in an ascent to orbit. However, there will still be some limitations in testing. For example, reflected shock tunnels are limited in their ability to perform combustion tests above the Mach 12-14 region because they produce higher levels of oxygen dissociation (50% at Mach 16) than would be expected during actual flight conditions.

Box 5-C—Limits of Computational Fluid Dynamics

Turbulent phenomena present a sometimes intractable problem for researchers attempting to model gas flows using numerical techniques. While the time evolution of some types of gas motion is predictable, turbulent flows are chaotic and only their gross behavior is amenable to computational analysis. A hallmark of turbulent flow is the presence of disordered motion at all scales. For example, the swirls and eddies of a rising column of smoke contain smaller-scale disturbances, and these enclose smaller ones, and so on. Unfortunately, to understand the large-scale behavior of turbulent motion, it is sometimes necessary to include the effect of the small-scale disturbances.

A faster computer can simulate turbulence at smaller scales, but the practical limits set by storage and speed limit how well any computer can predict flow patterns. For example, if the numerical simulation of a turbulent flow requires calculations every one tenth of a millimeter, then enormous requirements would be made on computer storage.[1] To make their calculations more tractable, computer models of airflows that include turbulence can resort to simplifying assumptions, such as assuming two-dimensional instead of three-dimensional flow. Another simplifying assumption is to neglect the "real gas" effects of chemically reactive species formed in hypersonic airflows. Unfortunately, full three dimensional models that include real gas effects are necessary to predict the aerodynamics and aerothermal loads that a particular airframe and engine configuration will experience in hypersonic flight.

Outside the engine, the most important limitation of CFD is in its ability to characterize the "boundary layer transition." The location and length of the transition from laminar (smooth) to turbulent flow—the boundary layer transition—has a significant impact on all aspects of engine and vehicle performance. For example, it affects the lift and drag on the vehicle, the airflow into the engine, and heat transfer rates. Assumptions about the location of the boundary layer transition therefore have a profound effect on design requirements for the propulsion system and the cooling system.

Although CFD researchers report progress in predicting the location of the boundary layer transition, complete validation of computer models is not possible using only ground-test facilities. NASP designers are making what they describe as conservative assumptions regarding the flow patterns over the X-30 to minimize the effect of boundary layer uncertainties in the performance of prospective vehicles. The boundary layer problem is another illustration of the difficulties engineers have in designing a vehicle meant to explore the outermost regions of the atmospheric flight envelope. It has also fueled disputes over whether the NASP philosophy of attempting to reach orbit without first building an intermediate vehicle(s) is excessively risky.

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[1] Edwin Galea, "Smoking Out the Secrets of Fire," *New Scientist*, July 7, 1988, p. 46. See also Edwin Galea, "Supercomputers and the Need for Speed," *New Scientist*, Nov. 12, 1988, pp. 50-55.

and resources. Instead of a subscale hypersonic test program, the JPO envisions using the X-30 as a flying test-bed to validate scramjet performance at high Mach numbers.

POLICY CONSIDERATIONS

As summarized in earlier sections, the NASP program is currently developing the technology to build an X-30 research vehicle. When this work is complete, the NASP joint program office will report to the Administration and to Congress on the feasibility, timetable, and costs of proceeding with development.

Proponents of the NASP program argue that it would maintain U.S. leadership in competitive technologies critical to the aerospace industry. Furthermore, they assert that the NASP program will lead to hypersonic aircraft and space launch vehicles that would have revolutionary capabilities. However, the Secretary of Defense and other DoD officials have suggested that because the NASP program is a high-risk program whose applications are long-term, it can be deferred in an era of stringent budgets.[38] This section presents several important considerations for Congress as it deliberates the future of the NASP program in relation to other civilian and military space priorities.

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[38] Craig Covault, "White House Acts to Reverse Aero-Space Plane Cancellation," Aviation Week and Space Technology, Apr. 24, 1989, pp. 20-21.

What future vehicles and mission capabilities could the NASP program lead to, and how would these compare with other alternatives?

The NASP program is designed to demonstrate technologies that could lead to operational launch systems for both military and civilian use in the early part of the next century. Assuming the X-30 were to complete its test program successfully, the first operational vehicles derived from NASP technology would likely be military launch vehicles, or perhaps military hypersonic cruise vehicles. An aerospace plane designed for military use could also be used for a variety of civilian applications, including transporting people to and from the proposed space station.

Even if the X-30 proves successful, launch vehicles or hypersonic aircraft derived from NASP technology would have to compete for funding and attention with other means of accomplishing the same military and civilian missions. If Congress believes that the NASP program should proceed only if it would lead to cost-effective operational vehicles, it may wish to examine the results of applications studies before funding Phase III of NASP. Alternatives to piloted NDVs would include expendable launch vehicles, other reusable concepts that include two-stage-to-orbit vehicles, and supersonic aircraft. An unmanned version of a NASP-derived vehicle is still another possibility. Because of their projected high unit costs, NDVs could not be procurred in large numbers. The NASP program office is comparing the utility of a military aerospace plane against alternative systems for carrying out the same missions. In addition to evaluating how well a small fleet of NDVs might perform versus a larger number of less costly systems, it will also be important for these studies to include both the effect of the long lead time for development of an NDV (operational vehicles are unlikely before 2005) and the effects of probable countermeasures.

Three classes of NASP-derived vehicles are possible:

Option 1: A Military Aerospace Plane

Endo-atmospheric hypersonic aircraft based on NASP technology could perform a variety of global military missions requiring rapid response, including reconnaissance,[39] interdiction, air defense,[40] and air strike. The NASP program has developed preliminary designs for hypersonic military aircraft with ranges from 12,000 to 17,000 nautical miles at speeds of between Mach 7 and 12.[41] Similarly, the second type of military vehicle that could be developed—a survivable, quick-response Mach 25 vehicle with access to space—would also have unique military capabilities.

The relative importance of these capabilities rests on a number of factors, including the comparative costs and capabilities of alternative systems. For example, small launch vehicles developed for DARPA's Lightsat program, which could provide responsive surveillance by placing small dedicated satellites in orbit to be used by field commanders, might compete directly with the capability of launch vehicles developed from NASP technology.[42]

Other potential missions for a NASP-derived vehicle (NDV) may depend on the continuation of a Strategic Defense Initiative with a space-based component. For example, although an operational spaceplane could not substitute for the Advanced Launch System heavy-lift vehicle being sought for some Strategic Defense System (SDS) payloads, it might be capable of economically launching smaller SDS payloads, such as space-based interceptor satellites, on demand. In addition, a spaceplane could be valuable for on-orbit maintenance of SDS satellites.

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[39] A hypersonic vehicle developed from X-30 technology might extend the speed and altitude limits of the Mach 3+ SR-71 "Blackbird," and could enable operation from more locations with faster response and improved turn-around times.

[40] An effort to develop hypersonic weapons for air defense is being conducted as part of the Air Defense Initiative (ADI), a DoD/DARPA program to counter the threat from low-observable bombers and cruise missiles. One application being studied is the feasibility of combining new surveillance methods with hypersonic, long-range surface-to-air missiles to attack aircraft carrying air-launched cruise missiles at long distances. Current air defense interceptors could not travel fast enough to reach such cruise missile carriers before they were within range of the United States, even if they were detected at the maximum range of new over-the-horizon radars.

[41] NASP Joint Program Office, personal communication, April 1989.

[42] U.S. Congress, Office of Technology Assessment, *Alternative Spacecraft Design and Launch Options*, OTA Background Paper, (Washington, DC: U.S. Government Printing Office).

Option 2: Civilian Aerospace Plane

A launch vehicle derived from NASP technology is one of several concepts being considered for low-cost piloted space transportation to and from low-Earth orbit. As part of its Advanced Manned Launch System (AMLS) Studies, NASA is studying reusable rocket-powered vertically launched vehicles and airbreathing/rocket horizontal takeoff systems as Shuttle replacements (see ch. 4). In part because of its simplified launch operations, a vehicle requiring only a single stage to reach orbit may have a greater potential to lower operating costs than two stage AMLS vehicles. However, a single-stage vehicle would also require use of more advanced technology (e.g., scramjet propulsion and new materials), and its development would be inherently more risky.

NASP shares some similarities with concepts for an AMLS, but it has important differences as well. Even though both programs will use new technology in areas like materials and structures, and both plan to incorporate autonomous vehicle operations to reduce launch and operation costs, building an aerospace plane requires a much larger technical leap than building rocket-powered launch vehicles. **Even assuming a rapid resolution of the myriad of technical issues facing the construction of an X-30, translating this technology into an operational spaceplane might come late in the period when an AMLS could be ready, and perhaps after the time when replacements for the shuttle will be necessary.** Presumably, an AMLS program that began in the late 1990s would still allow for completion of an operational vehicle by the year 2010. An AMLS program begun in that time might also benefit from matured NASP technologies, especially in the area of materials and structures.

Prospective first-generation operational follow-ons to the X-30 would almost certainly have less payload capacity than the present Shuttle.[43] They would compare favorably with possible AMLS vehicles (roughly 20,000 to 40,000 pounds into low-Earth orbit). An NDV might be used for civilian applications even without large payload capacity. These could include satellite launch, responsive satellite replenishment, on-orbit maintenance and repair, ferrying of astronauts and cargo to the proposed space station, and serving as a space rescue vehicle.

The cost-effectiveness of these missions should be evaluated in comprehensive applications studies that evaluate the feasibility of using alternative launch vehicles and assess future civilian launch needs. For example, the feasibility of on-orbit maintenance would depend on the operation and support costs of a NASP-derived vehicle and on satellite design. At present, the costs of on-orbit retrieval or repair generally far outweigh the costs of building new spacecraft.

Option 3: Orient Express

Perhaps mindful of the popularity of NASA's piloted space-flight program with the public, some proponents of NASP have made exaggerated claims regarding the civilian benefits of the X-30 program, especially those pertaining to the commercial transport dubbed the Orient Express. Such claims have abated and program managers now appear to be sensitive to the dangers of overselling their program. NASP officials were forthright in explaining to OTA that their program has little to do with creating an Orient Express.

If a Mach 5+ commercial transport is developed, it will likely evolve from NASA's High-Speed Commercial Transport Program. Such a vehicle, currently thought to compare unfavorably in cost and environmental acceptability[44] with slower supersonic transports that would fly between Mach 2 and 3, would benefit from the advanced technology being developed for the X-30. However, as emphasized earlier, the X-30 program is neither the most cost effective nor the most direct route towards facilitating hypersonic civilian aircraft.

In the mid to late 1990s, Congress will have to choose among the competing claims of proponents of a variety of new launch systems, including

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[43] Roughly 55,000 pounds when launched East into a circular orbit 110 nautical miles high.

[44] However, as noted earlier, hypersonic transports would fly at very high altitudes and their exhaust products might not endanger the ozone layer. Sonic boom effects might also be reduced by high altitude flight.

NASP-derived vehicles. If the NASP program achieves its technical goals and can demonstrate the potential for low operational costs, launch systems derived from NASP technology may well replace other prospective launch systems. However, the life-cycle costs, which include development, acquisition, and operations costs of each system, will have to be examined and compared in order to choose the best launch system mix.

What Auxiliary Benefits Could the NASP Program Provide?

By providing a focus for defense research and development on the technologies of hypersonic flight, NASP and follow-on programs could make important contributions to defense programs seeking long-range, fast weapons delivery. For example, an obvious area for coordination in weapons development is the very long-range hypersonic surface-to-air missile being sought by DARPA and the Air Force for applications such as air defense, fleet defense, and long-range targeting of mobile and relocatable assets.[45]

Proponents of the NASP program maintain that it would contribute important new technology to the defense technology base.[46] Although it is clear that the NASP program has contributed to the Nation's ability to manufacture new lightweight materials capable of enduring high thermal and mechanical stresses, has improved computational fluid dynamics techniques, and has advanced the theory and application of hypersonic propulsion, it is too early to assess how much these technologies will benefit defense programs outside of NASP.

The long-term benefits of the NASP program to civilian industry may also be substantial, but they too are uncertain. Proponents of the NASP program believe it would have important benefits in many of the high-technology industries of the next century. In particular, they believe that the program would have great benefit for the civilian aerospace industry. However, other programs, such as a high-speed commercial transport program, would also have the potential to enhance the U.S. competitive position in the civilian aerospace industry, and might do so more directly than the NASP program.

Is the NASP Program Technically Sound?

OTA did not conduct a detailed assessment of the technical soundness of the NASP program. Two advisory bodies, the Defense Science Board (DSB) and the Air Force Studies Board (AFSB) of the National Research Council, have conducted recent technical reviews.

The DSB report. In 1987, the DSB performed a comprehensive technical review of NASP. Members of a special task force said they were impressed by the progress the NASP program had made. However, they were cautious in their outlook and warned that they were "even more impressed by what has yet to be done to reduce the remaining uncertainties to a reasonably manageable level."[47] The DSB study was conducted early in the technology development phase of the NASP program (Phase II) and overlapped internal reviews by project management that also concluded that some redirection of program efforts was desirable. Appendix E presents an overview of the DSB report and its impact on the NASP program.

In response to the DSB report, officials in the NASP program adopted a "Risk Closure Program," a plan to remove uncertainties in the X-30's component technologies systematically by mapping out in advance a series of technical achievements that must be attained to achieve program objectives. NASP officials have stated that they will not recommend a transition out of the current Phase II research stage unless the risk closure effort is substantially complete.[48] At that time, they believe the technical risks in moving to Phase III will center primarily around technology supporting high-Mach scramjet propulsion.

Program managers assert that they have made rapid progress in developing the key enabling technologies for propulsion systems, materials and structures, and computational fluid dynamics since the DSB report (app. E). They have also revised designs for the X-30 to use technology possessing lower risk, albeit at penalties such as an increase in vehicle gross take-off weight.

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[45] However, to make these missions practical there is also the necessity to develop near real-time surveillance or other intelligence methods to guide long-range weapons close to targets. At present this is an unsolved problem.

[46] OTA did not assess in detail the potential benefits of the NASP program to the Nation's defense technology base.

[47] Defense Science Board Report on the National Aerospace Plane, p.4.

[48] Statement by NASP JPO director Dr. Robert Barthelemy at OTA briefing, Dec. 13, 1988.

The AFSB report. The Committee on Hypersonic Technology for Military Application of the Air Force Studies Board was formed to evaluate the potential military applications of hypersonic aircraft and assess the status of technologies critical to the feasibility of such vehicles. Part of the Committee's task was to advise the Commander of the Air Force Systems Command on the research and development strategy of the National Aero-Space Plane. The AFSB report followed the DSB report, and there was some overlap in membership of the two committees. Full committee meetings were held from April 1987 through March 1988.

The Committee recommended that the NASP program office retain the ultimate goal of demonstrating the technical feasibility of reaching orbit with a single propulsion stage, but, like the DSB, expressed many concerns about the maturity of the technologies that would be necessary to meet this goal. In particular, the Committee felt that progress in materials and structures would be a probable limiting factor in meeting the JPO's primary objective of demonstrating single-stage access to orbit.

The Committee also made a number of recommendations that would aid in the development of a broad and aggressive research program into the enabling technologies of hypersonic flight. For example, it found an urgent need for the construction of a new hypersonic wind tunnel that would permit testing of hypersonic configurations at close to full-scale conditions through Mach 10. A "quiet" wind tunnel was recommended because of its capability to simulate with good fidelity crucial phenomena such as the boundary layer transition.[49]

The Committee agreed that a flight-test vehicle was both desirable and necessary to complement ground-test facilities. However, uncertainties in the enabling technologies of the X-30 were sufficiently great in the Committee's view that they recommended that the NASP JPO retain an option to build a research vehicle that would not be designed to reach orbit. This recommendation is discussed later in Issue 4.

The decision to recommend a move into Phase III, the construction of the X-30, must be approved by the NASP Steering Committee, chaired by the Undersecretary of Defense for Acquisition. NASA's Office of Aeronautics and Space Technology Administrator serves as vice-chair of the Steering Committee. If approved, the final decision on whether or not to fund development of a flight vehicle would then be made by the Administration and the Congress.

How risky is the NASP development strategy?

This discussion assumes that the NASP program will continue to exist as a development program, leading to an X-30 research vehicle. Recent decisions within DoD cast doubt on that assumption.[50] The potential effects of a range of budget options are discussed below in Issue 6.

Option 1: Go Slow In Phase II?

NASP officials plan to use the X-30 as a flying test-bed that will first explore the hypersonic flight regime and then attempt to reach orbit. NASP program managers face the fundamental choice between attempting to design and build the X-30 as soon as possible, or going slower in Phase II with the expectation that more advanced technologies would lower the risk of subsequent performance shortfalls. Both paths have advantages and risks.

If the X-30 is able to reach orbit with a single stage, it will have achieved a remarkable goal, one that could revolutionize launch concepts. However, if engineers are forced to design a vehicle with little flexibilty or little performance margin in order to meet the objective of SSTO, they would face severe cost restrictions should subsequent design modifications prove necessary. Modifying sub-scale models in ground facilities would be much easier and cheaper than attempting to make modifications in a flight vehicle. A longer ground test program could reduce the risk of failing to meet program goals and might also allow the incorporation of more advanced technology. Yet, stretching out the Phase II program could raise the costs of technology development and lead to loss of interest in the goal of building an X-30 test vehicle.

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[49] According to the AFSB, a quiet wind tunnel would minimize disturbances to gas flow that emanate from wind tunnel settling chambers and acoustic radiation from nozzle wall boundary layers.

[50] In April 1989, the Secretary of Defense decided to cut funding of the NASP program dramatically and recommended that the program be transferred to NASA. However, other decisionmakers, including members of Congress, will also shape the future of the NASP program.

NASP officials have chosen to use the Phase III decision point[51] to decide whether or not to build the X-30. The possibility of stretching out Phase II, or moving to some intermediate developmental phase that might allow some full-scale component construction and testing without actual assembly of an X-30, is not a formal option in current plans. Officials believe that slowing the pace of the program at this time is unnecessary and would prove to be wasteful. In a fiscally constrained environment they may also be responding to the perception that research and development programs that have mostly a long-term payoff are especially vulnerable to budget cuts.

Option 2: Build A Series of Vehicles?

The NASP JPO plans to use the X-30 as both a research vehicle, which would acquire test data at hypersonic speeds, and as a demonstration vehicle, which would fly to orbit and cruise within the atmosphere at hypersonic speeds. In some respects, these goals may conflict with one another.

The AFSB report expressed concerns over the performance of the scramjet propulsion system at high Mach numbers. In order to ensure that the X-30 is able to reach the high Mach numbers critical to testing scramjet designs, it recommended that the X-30 incorporate auxiliary rocket propulsion to enable controlled flight with some independence from the air-breathing propulsion system. In addition, the AFSB recommended that JPO consider fabricating a series of flight research vehicles that would incrementally explore the flight regimes of a SSTO vehicle.

This strategy could have at least two advantages. First, it could lower the risk of "failure." Some analysts believe that an X-30 that could not meet its promised objectives, especially single-stage access to space, would risk reducing, or even ending, government interest and investment in hypersonic technologies. Second, it might aid researchers by allowing them to design a better test vehicle. For example, a vehicle that was not designed to reach orbit could use the relaxed materials and propulsion system requirements to fabricate a less expensive vehicle that might be easier and cheaper to instrument and reconfigure during testing. Fabricating a series of aircraft that would culminate in a SSTO spaceplane might be more costly than building the X-30 directly. However, it might also spare the necessity of a costly modification program if the X-30 failed to achieve its design objectives. In summary, a program management strategy that built a series of test vehicles might allow researchers to "learn to crawl before they learn to walk."

NASP officials have rejected the idea of an intermediate vehicle on a variety of technical grounds, including the difficulty in extrapolating data acquired at lower Mach numbers to design a single-stage-to-orbit, Mach 25, vehicle.[52] Furthermore, they dispute the contention that an X-30 designed to achieve orbit conflicts with its role as a technology test bed. For example, they note that the X-30 would carry sufficient payload capacity to carry a full complement of instrumentation.

Officials also believe that the X-30 would have ample margin to reach orbit and serve as a research vehicle, especially if an option to build an X-30 with additional payload capacity is exercised. They also believe that an X-30 designed with rocket thrust augmentation would be almost certain to reach the high Mach numbers desired for scramjet tests. NASP contractors also disputed the claim that the X-30 is excessively risky. For example, Pratt & Whitney and Rocketdyne officials claim their engine designs allow considerable flexibility in engine geometry without an excessive number of moving parts.

While not explicitly acknowledged by NASP officials, the decision over which development strategy to pursue also affects future support for the program. NASP officials report that a survey of potential military users for a Mach 8 to 24 hypersonic cruiser found relatively little interest in this vehicle compared to one that could demonstrate an ability to reach orbit. In a limited funding environment, NASP officials may well fear that a multistage program to step up to Mach 25 incrementally would not be funded, regardless of the technical risk. In addition, the cost of building a series of flight vehicles would be higher than building an X-30, if, as implicitly assumed, the X-30 is able to meet program objectives without costly modifications to its original design.

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[51] Under current plans and funding profiles, this would likely occur in September 1990.

[52] An intermediate vehicle might support a two-stage design with an air-breathing bottom stage, but two-stage vehicles are not being considered in the NASP program. Two-stage vehicles are being considered in NASA's AMLS studies.

NASP program managers have a delicate task as they balance the advantages of deciding to move into Phase III, in order to maintain DoD and NASA support, against the risks of selecting an X-30 design that might later fall short of expectations and even impede future hypersonic technology development. Congress may well wish to explore the advantages and shortfalls of both approaches as it debates whether or not to fund development of the X-30 when the current Phase II program is completed.

How much will Phase III of the NASP program cost?

The NASP program has already cost about $800 million in Federal funds and $500 million contributed by industry, exclusive of "infrastructure" costs, such as Air Force and NASA salaries, and overhead costs for facilities. NASP officials have stated that a continuation of funding close to the Phase II requests ($427 million for fiscal year 1990) will be sufficient to both meet the technology goals set out in the Risk Closure Plan and to support a Phase III decision in late 1990.[53] Current estimates for Phase III costs are very uncertain because they are based on extrapolations from designs now viewed as overly optimistic.[54] This uncertainty is compounded by the inherent difficulty in projecting costs for an aircraft as novel as the X-30. Recent experiences with high-technology programs, such as the B-2 bomber, suggest cost growth in Phase III is a very real possibility. The NASP JPO is preparing detailed cost estimates for their Phase III review, but preliminary figures will not be available until the fall of 1989.

Whatever the estimates, the fabrication and testing of a flight vehicle in Phase III of the NASP program would require substantial increases in funding over current expenditures. Even without unforeseen cost growth, the NASP budget, as currently projected, will rise from the current level of approximately $320 million to about $500 million in fiscal year 1991. Peak expenditures are expected in fiscal years 1992-1994, when spending is projected to rise to approximately $550 million per year. As a practical matter, funding for Phase III will depend on convincing the Administration and Congress that operational follow-on launch systems show sufficient promise to continue the program. In all likelihood, Air Force support will be essential.

What would be the options for the NASP program if its budget were cut?

As the NASP program nears the end of its technology maturation and concept validation phase, it is coming under increasing scrutiny by lawmakers and defense officials already struggling with steady or declining defense budgets. The revised DoD budget submitted by Secretary of Defense Cheney in April 1989 cut DOD funding for NASP from $300 million to $100 million. DoD would contribute no funds in subsequent years. In addition, the Secretary proposed to transfer responsibility for managing NASP from DoD to NASA and allow NASA to obligate the $100 million of fiscal year 1990 DoD funds.

The proposed cuts and change of management has accelerated a review of the NASP program. Yet, many of the important tests that would be needed to support an informed decision on the technical feasibility of the program are scheduled to be performed in fiscal year 1990, the last year of Phase II. Furthermore, the critical applications and cost studies are not yet complete.

Congress has three broad options on funding for NASP:

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[53] Dr. Robert Barthelemy, cited in "One On One," *Defense News*, Oct. 24, 1988, p. 46.

[54] Early baseline NASP vehicles envisioned a 50,000 pound take-off gross weight vehicle ("Phase III Alternatives: Contractor Findings," *National Aero-Space Plane Program Briefing to NASP Steering Committee*, Nov. 7, 1988, p. 49) and only air-breathing propulsion from a standing start to Mach 25. Current NASP designs plan to use less exotic materials; the vehicle is much larger and heavier; and, as noted earlier, designs include options to carry on-board liquid oxygen to augment air-breathing engines or fuel a separate rocket propulsion system.

Option 1: Continue to fund the program at or near the original requested rate.

Under this option, NASP would receive $300 million from DoD and $127 million from NASA in fiscal year 1990. Funding of this level ($427 million) would allow the NASP program to continue its Phase II research program and to complete its application and cost studies by the end of the fiscal year. At that point, the Administration and Congress could then decide whether or not to build two X-30 test vehicles.

A decision to continue planned funding of the program would ensure that the contractor teams and the materials consortium were maintained for another year. Even if the Administration and the Congress decided to delay development of an X-30 for several years, the Phase II findings and technologies would be available for a later effort. In addition, the technologies developed in Phase II would be available for other purposes.

If Congress were to restore funding of NASP to a level of roughly 75 percent of its original request, and if the current management arrangement were retained, the Phase III decision would likely slip by a year or so, depending on the size of the cut. Although the program would then risk losing momentum and industry support, testing and evaluation could proceed in an orderly fashion, and, in addition, the extra time might allow for the maturation of more advanced materials, and the refinement of computational fluid dynamics simulations.

Option 2: Accept the current DoD proposal for program cuts.

The DoD proposal would cut the DoD contribution by two-thirds in fiscal year 1990 and turn the program over to NASA. DoD would contribute nothing in subsequent years. Under this option, the NASP program would still be able to pursue important technology studies; however, the program would not focus on the development of a flight vehicle.

With only $100 million of DoD support, and assuming NASA funding did not rise (in fact, a cut in funding would be likely), a decision on whether or not to construct a flight vehicle might be delayed 3 to 4 years. The program would probably need to be transfered back to DoD in the mid-1990s in order to proceed with a test aerospace plane, because NASA has little incentive to build an X-30 on its own. If managed by NASA, the program would compete directly with funding for alternative launch systems such as AMLS and also with the Space Station program, which, along with the Space Shuttle, will command most of NASA's resources for at least the next decade.[55]

The NASP program currently enjoys broad support and financial committment from industry because it is focused on building a flight-test vehicle that could lead to the production of operational vehicles. If the program is restructured into a technology maturation program only, as would likely occur if the program is transferred to NASA and DoD funding is ended, much of what has become a national technology base could be lost. Moreover, there is the risk that a future decision to develop a hypersonic flight-test vehicle would not be supported by industry. The importance of industry support for NASP should not be minimized. In fact, NASP officials believe their greatest accomplishment to date has been the marshaling of the talents of thousands of the Nation's most talented scientists and engineers, and the creation of innovative industry teaming arrangements. Recreating this base of expertise would be both costly and time consuming.

Option 3: Cut funding entirely.

If Congress feels that the long-term goals of the NASP program are less important than other pressing priorities in the Federal budget, it could decide to terminate funding entirely and close the NASP program out. However, some funding would have to be supplied to complete contractual obligations already made. In addition, unless contractors were able to continue their work to a logical conclusion, much of the progress made in the program would be lost.

The diversity of its potential benefits has given NASP a broad base of support; however, a decision to move beyond the concept validation phase of the program will require a demonstration that the program is technically sound and that it has adopted a prudent management strategy. As a practical matter, the high costs to build and test a flight vehicle imply that Service support, most likely from the Air Force, will be necessary.

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[55] U.S. Congress, Congressional Budget Office, The NASA Program in the 1990s and Beyond (Washington, DC: Congressional Budget Office, May 1988).

Chapter 6

Escape and Rescue Vehicles

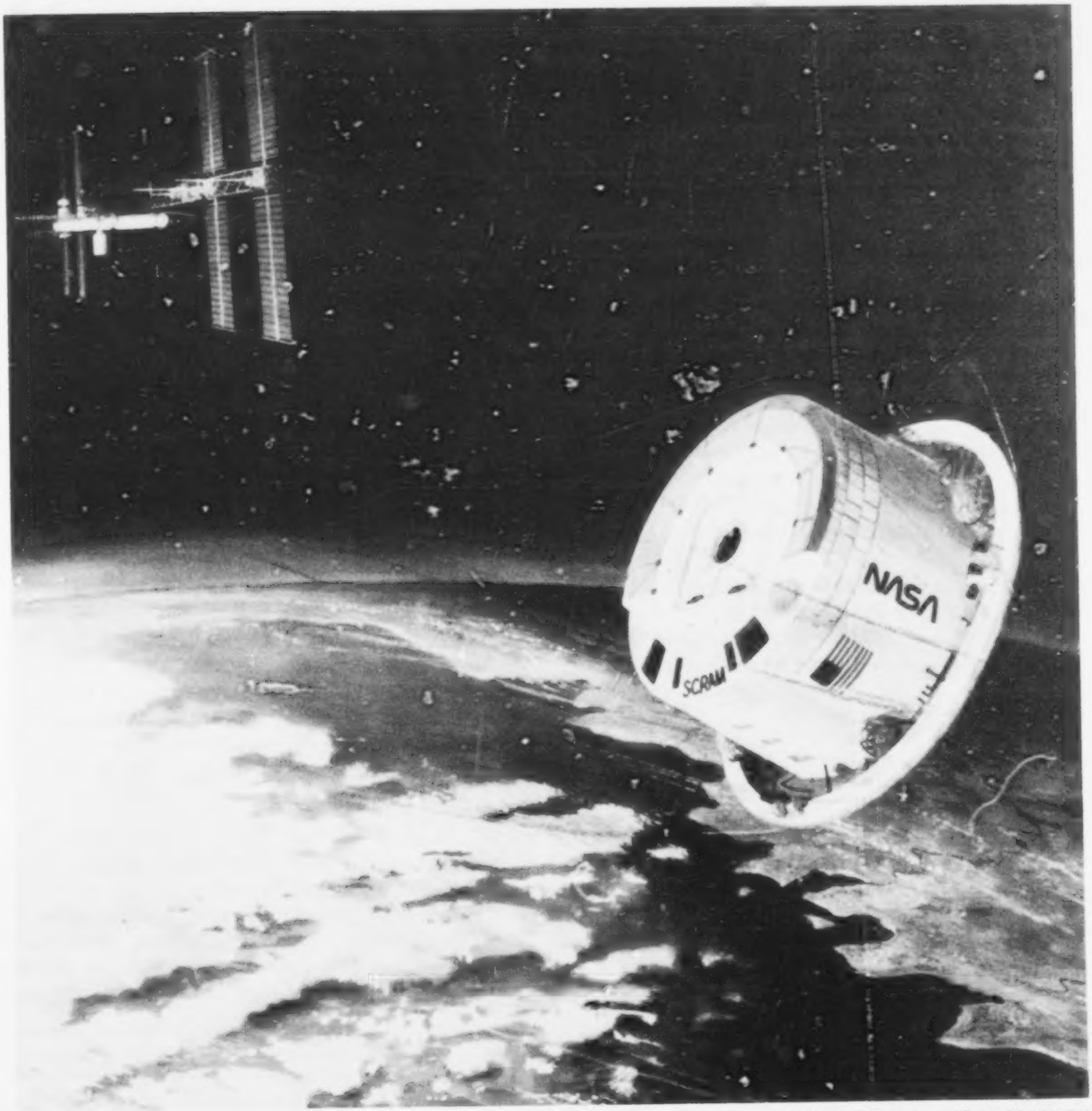

Photo credit: National Aeronautics and Space Administration

Artist's conception of a capsule-type escape vehicle after it has just left the international Space Station.

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Chapter 6

Escape and Rescue Vehicles

INTRODUCTION

Several contingencies could arise that would require the emergency escape or rescue of personnel in space. These include medical emergencies of Space Station crewmembers, major equipment failures, or damage from orbital debris. Rescue might also be necessary if the Shuttle failed to meet its scheduled launch date by so long that the Station was in danger of running out of critical supplies.

The U.S. space community is investigating the need for a means of crew rescue or escape[1] from the Space Station, independent of the Space Shuttle. **As noted in chapter 3, the existing Space Shuttle system is neither robust enough nor reliable enough to support continuously, at low risk, the needs of Space Station crew during deployment and operations.** The Space Station may need a "lifeboat," a capsule kept at the Space Station for emergency escape to Earth, or a rescue vehicle kept ready on a launch pad on Earth.

SPACE STATION CREW SAFETY

The National Aeronautics and Space Administration (NASA) has studied several Space Station safety and emergency management options, including building "safe havens," with limited on-board medical support, and resupply/rescue by the Shuttle (see figure 6-1). Because a rescue by the Shuttle could take several weeks, NASA has also investigated options for an assured crew return capability (ACRC).[2]

The Space Station itself will be designed to provide Station crew with safe havens during emergencies. Methods for assuring maximum possible safety include: providing the means to seal off modules or systems experiencing failures, fires, or breaches; providing all modules with at least two exits; and placing emergency supplies in each section to sustain any trapped or isolated crew. The safe haven approach could also be extended to include an ability to leave a crippled Space Station and seek temporary refuge in an independent orbiting facility until rescue could be initiated from Earth.

NASA is assessing two categories of ACRC options: 1) escape vehicles based at the Space Station that could respond within hours, and 2) ground-based rescue vehicles that would be independent of the Shuttle and potentially more responsive than the Shuttle to an emergency. These ACRC options include:

- a new ground- or space-based emergency return vehicle;
- a ground-based Shuttle ready to be launched on demand;
- an orbiter, modified as necessary, for extended on-orbit stay time to be docked at the Space Station;
- unpiloted Shuttle launch with automated or remote control capability for rendezvous operations;
- ELVs to resupply Station crew for an indefinite period, possibly in conjunction with an orbital manuevering vehicle (OMV);
- modifications to the Station safe havens, which may enhance the other five options.

NASA has characterized the need for an escape or rescue capability by defining three possible scenarios ("design reference missions") that would require some or all Station crew to return to Earth before a Shuttle could be dispatched to rescue them.[3] NASA has estimated some of the probabilities that these or other emergencies might occur. However, it has not characterized the probabilities of other scenarios in which a rescue capability would **not** help—for example, loss of an orbiter carrying crewmembers for the Station during ascent on a

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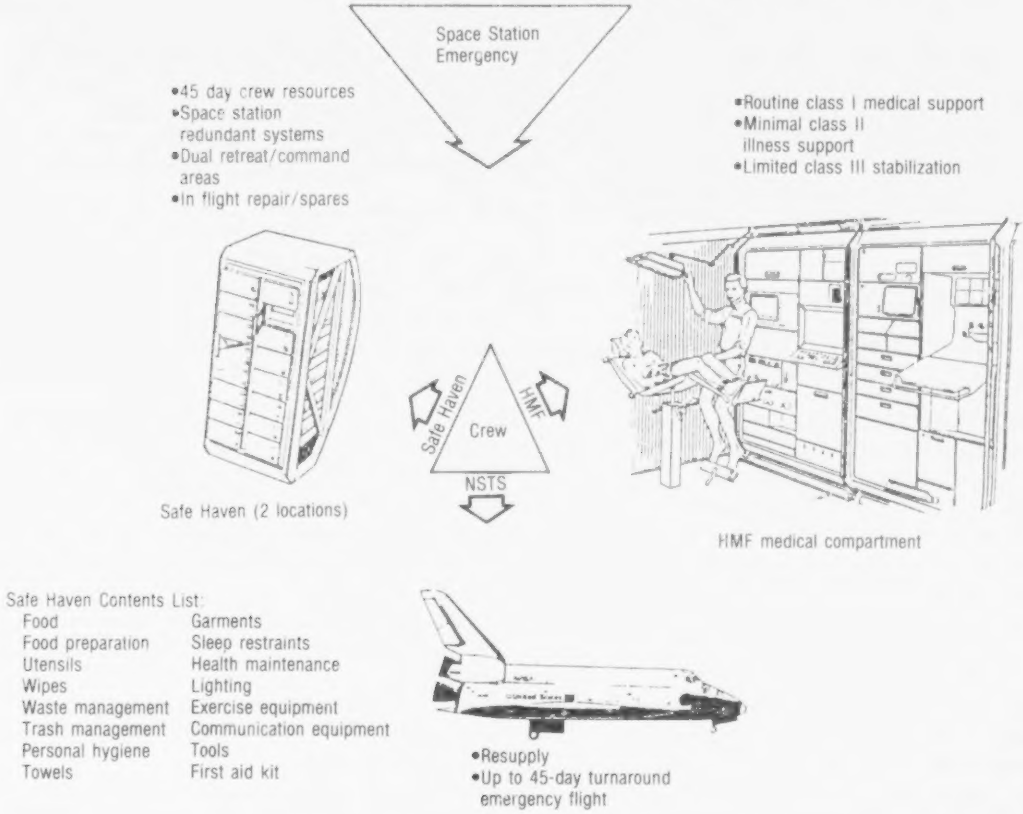
[1] As used in this report, crew escape implies return from the Space Station in a capsule or vehicle docked at the Station, while rescue implies sending up an Earth-based vehicle (piloted or unpiloted) to retrieve crew members.

[2] Also known as Crew Emergency Rescue Vehicle (CERV) options. NASA completed Phase A work on the CERV concept in December, 1988. NASA expected to issue an RFP in April 1989 for further studies of CERV for the Space Station, which would focus on more specific concepts. After this study, a follow-on contract was supposed to be awarded for Phase B work. These plans have been placed on hold, however, until after the NASA FY90 budget request is acted upon.

[3] See "ACRC-CERV Phase A Report," NASA Johnson Space Center, JSC-23321, Dec. 23, 1988, sec. 1.4.1, Space Station Crew Safety Alternatives Study, p. 4-7.

Figure 6-1—Space Station Emergency Management



KEY: HMF = health maintenance facility; NSTS = national space transportation system.

SOURCE: National Aeronautics and Space Administration, Johnson Space Center.

crew-rotation mission and its affect on total mission risk.[4]

It may be, for example, that the risks Station crewmembers face are dominated by the risk of ascent on the Shuttle, in which case investment in an alternate crew return capability would reduce the risks of reaching and living on the Space Station only marginally. To decide whether a risk-reducing effort is worth the substantial investment required, Congress must be advised on how much the investment would reduce the risk.[5] Even if an alternate crew return capability were provided and worked as planned, it would not eliminate all risks to station crewmembers. In deciding whether or not to fund development of a crew escape vehicle, Congress may wish to ask NASA to conduct an analysis comparing the risks faced by crews living on the Space Station to those of reaching the Space Station and returning to Earth.

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[4] NASA does not routinely carry out probabilistic risk analysis of its space systems. Trudy E. Bell and Karl Esch, "The Space Shuttle: A Case of Subjective Engineering," *IEEE Spectrum*, June 1989, pp. 42-46.

CREW EMERGENCY RETURN

If, in the judgment of NASA officials and Congress, a risk assessment demonstrates the need for emergency crew escape, two basic options present themselves:

1. Simple *capsule designs* with an ablative heat shield reminiscent of the "Viking" and "Discoverer" reentry capsules from the early days of spaceflight. Also included in the capsule category, although it has a more extended "loiter time"[6] than those described above, is an Apollo derivative capsule that would also include an ablative heat shield (figure 6-2). Advantages of capsules include simplicity, relatively low cost, and proven technology. Capsule designs also need little or no piloting, which would be a major advantage. Requiring that a pilot be available at all times on the Space Station would be expensive and a questionable use of resources. In addition, pilots might become too weak to function as pilots after a stay in space of 20 or more days, making capsule designs desirable.
2. Small, aerodynamically stable *gliders* (medium lift/drag lifting bodies)[7] that can land by parachute or at low speed on a runway. A Crew Emergency Rescue Vehicle (CERV) configured for water recovery (figure 6-3) would provide a wider range of landing sites and greater time margins for reentry and recovery and a softer ride than capsules (important if an injured crew member is returning).[8] However, a glider would cost at least 20 to 30 percent more than the simplest chute version of a capsule.[9]

NASA has also considered a Space Taxi and Return (STAR) vehicle, which could serve several missions:

- crew emergency rescue or escape;
- assured crew access (an "up-CERV," which could complement the Shuttle);
- small logistics transport; and
- use as an on-orbit maneuver vehicle as shown in figure 6-4.

CERV or STAR spacecraft could be launched by Titan III or Titan IV launchers, an Advanced Launch System, or a booster based on a Shuttle liquid rocket booster. A Shuttle could put two crew rescue vehicles up at one time for docking at the Space Station. Which alternative is chosen depends on which options NASA chooses for the Personnel Launch System.

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[5] What is "acceptable" crew risk is, of course, an emotional issue. Those doing hazardous work on Earth, such as construction and mining, acknowledge risk and expect a certain number of fatalities on a project such as a bridge, skyscraper, or tunnel. Some feel that a hard look must be given at spending a few billion dollars to rescue (assuming it is even a survivable emergency) a few people at the Space Station. Any appropriations would have to compete with efforts that may be seen as saving more lives, such as research on cancer and infant mortality. (Tom Rogers, quoted in "Fleeing [Space Station] Freedom," by Richard DeMeis, *Aerospace America*, May 1989, pp. 38-41.)

Others believe that no matter what the cost-benefit analyses say, that a rescue craft is a necessity -

> The prospect of all the world seeing the ordeal of a stranded crew or a dying crew member nightly on television is chilling. The national nightmare of a crew in trouble with no timely way home, no matter what the chances of occurrence, is reason enough for many both within and outside of NASA to push for a rescue vehicle as a political necessity.

(Richard DeMeis, Ibid.)

[6] Loiter gives an indication of how rapidly a vehicle plummets towards Earth. Extended loiter allows more flexibility for landing during certain advantageous "windows" and greater crossrange, allowing for landings at more desirable locations.

[7] Some experts distinguish between gliders, which have true wings and provide a relatively high lift-to-drag ratio, and lifting bodies, which have no wings, and a lower lift-to-drag ratio.

[8] A glider would experience one to two g's while capsules would experience almost four g's for the Discoverer or Apollo shape, or seven g's for the Viking shape.

[9] Engineers at NASA Langley believe the differential to be 20 to 30 percent. However, other engineers that OTA consulted believe the differential could be even greater, perhaps 50 percent.

Figure 6-2—Design Reference Missions (DRMs)

Viking shape

- DRM: 1, 2 only
- 'Space ejection seat'
- Minimal loiter
- Simplest subsystems
- Water landing good boat

Discoverer shape

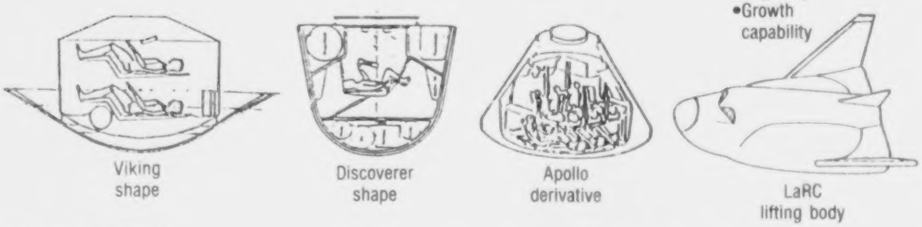
- DRM: 1, 2, 3
- Capable space vehicle with limited loiter
- Simple subsystems
- Water landing good targeting

Apollo shape

- DRM: 1, 2, 3
- Capable space vehicle with extended loiter
- Apollo-based subsystems
- Water landing good targeting

Proven shape

- DRM: 1, 2, 3
- Capable space vehicle with limited loiter
- Simple subsystems
- Water/land landing good targeting
- Growth capability

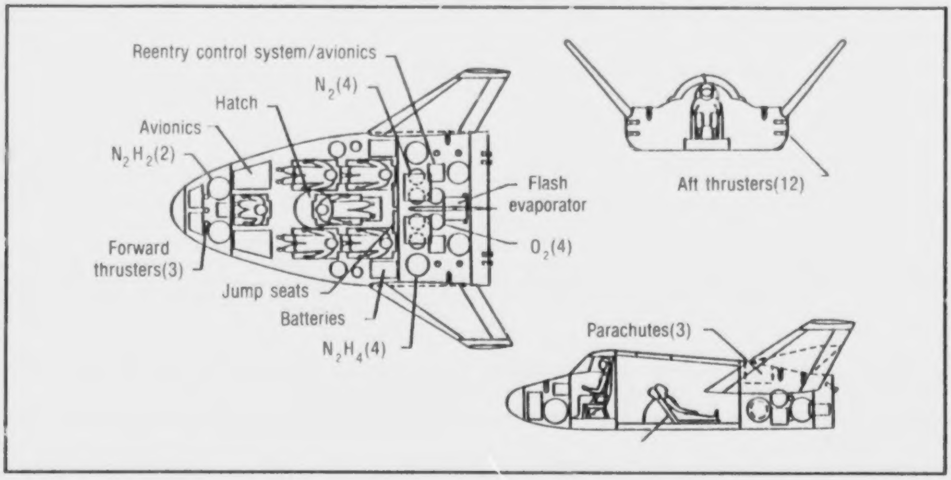


Design Reference Missions(DRMs)

- DRM1—Some problem makes shuttle not available in timeframe needed. Crew leaves when convenient.
- DRM2—Propagation of failure exceeds safe haven capability. Shuttle turnaround time exceeds need. Crew leaves immediate.
- DRM3—Medical emergency exceeds health maintenance facility capability. Shuttle turnaround time exceeds need. Crew leaves as soon as possible for desired landing zone.

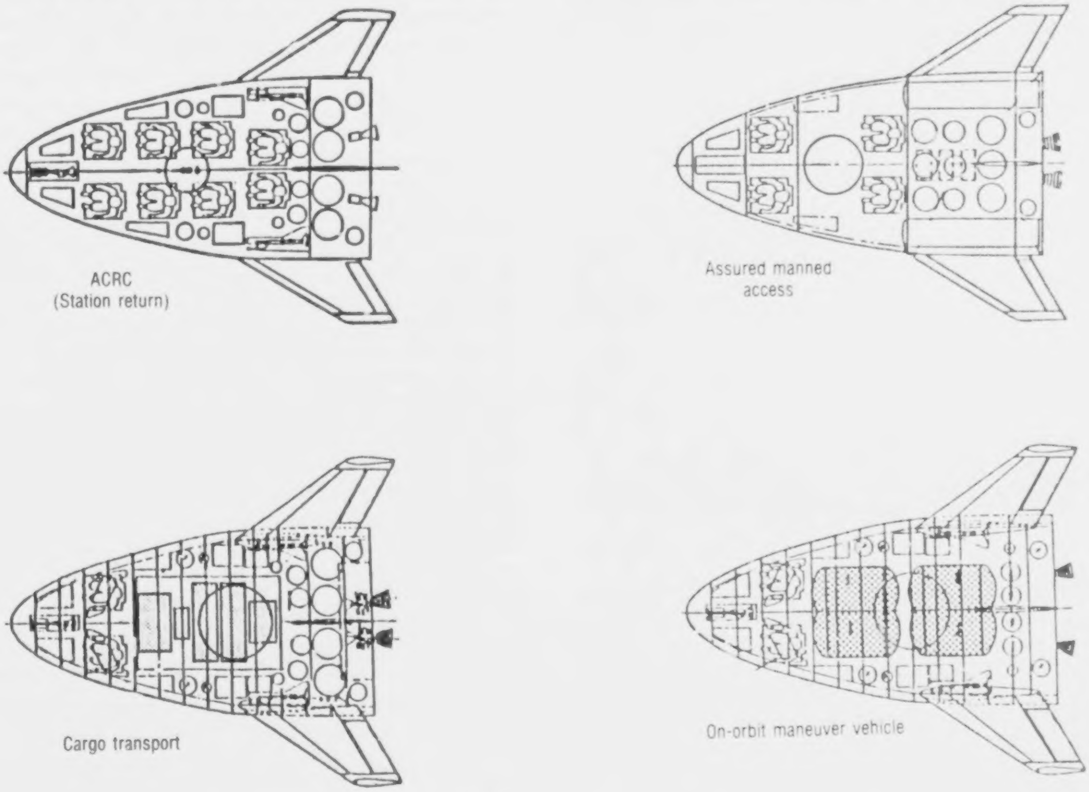
SOURCE: National Aeronautics and Space Administration.

Figure 6-3—CERV Glider Configured for Water Recovery



SOURCE: National Aeronautics and Space Administration, Langley Research Center.

Figure 6-4—Assured Crew Return Capability (ACRC)/Space Taxi and Return (STAR) Vehicle Options



SOURCE: National Aeronautics and Space Administration, Langley Research Center.

If the United States wants to develop an escape or rescue capability independent of the Shuttle, and if Space Station deployment remains on schedule, a decision should be made within the next 2 years concerning whether to pursue capsules or gliders. **The fastest, cheapest way to allow crew escape from the Space Station would be to dock reentry capsules of proven capability—shaped like NASA's Apollo or Viking capsules or the Department of Defense's Discoverer capsules—to the Space Station for emergency use.** Development costs could run between $300 million and $500 million. NASA estimates that development and testing of a capsule would take about 5 years. However, capsules have less development potential than gliders since gliders could be eventually upgraded to perform tasks other than crew escape.

As noted, glider development would cost more and would probably take longer (although it could still be ready in time for Space Station use). At even greater cost, NASA could procure extra Shuttle orbiters and keep one docked to the Space Station.[10] Other options might be available in the next century. For example, NASA could rely on "NASP-derived" spaceplanes[11] for crew rescue.

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[10] However, leaving the Shuttle at the Space Station would be expensive and have a major impact on the Station's operations and logistics. For example, there would be increased station drag and inertia changes that would require use of more attitude control fuel. The Shuttle itself would probably require major modifications to achieve long stays in orbit.

[11] These would probably not be available until 2010. See ch. 5.

Photo credit: National Aeronautics and Space Administration

Artist's conception of a glider-type escape vehicle about to touch down at sea after reentry.

DOCKING ISSUES

As noted above, one or two escape vehicles could be docked at the Space Station or a rescue vehicle could wait on a launch pad[12] on Earth. Both basing modes have their proponents. An escape vehicle docked at the Station could be used rapidly. NASA estimates that emergency response times would range from 17 minutes in the best case to 48 minutes if an accident occurred while crew was involved in extra vehicular activity.[13] Once the escape vehicle is freed, it could be launched towards Earth as soon as a landing window is available.[14] However, an escape vehicle might be sitting idle in the space environment for long periods of time—up to 2 to 4 years—which could adversely affect its reliability.[15]

Basing a rescue vehicle on a launch pad could provide added flexibility for rescue, for example, to send personnel or supplies to the Space Station, to provide medical assistance, maintenance, or to dispatch a replacement crew. Maintenance and replacement of critical systems is also easier when a rescue vehicle is based on Earth, but it could not be used for emergencies requiring quick response. The rescue spacecraft and its launcher would need a dedicated launch pad and would take a relatively long time to reach the Station and return. Under existing launch operations conditions, a launch vehicle would also take weeks to prepare, even if it were ready and able to use a dedicated launch pad. NASA has not estimated comparative costs or safety benefits for all of these options. However, pad basing does not meet NASA's medical requirement of returning a sick or injured crew member to Earth-bound medical care within 24 hours. Thus, NASA has decided not to pursue pad-basing concepts, although others believe that this option should remain open for further study.

OPERATIONS SUPPORT

Before committing to a rescue strategy, system designers will have to address the costs of developing the necessary support infrastructure and operating the chosen system. Because a rescue system, if built, would be needed for the life of the Space Station, its total recurring costs could easily exceed its development costs. Support infrastructure might include ground operations hardware and personnel at the mission control site, landing site crews located around the world, and the necessary subsystems and logistics support to resupply, replenish, and possibly repair a CERV on orbit. Depending on the detailed design of the CERV, each of these factors can seriously influence the operational characteristics and costs of the system.

As illustrated by the Space Shuttle, operating costs can constitute a major component of the life-cycle costs of a system.[16] Decisions made early in the development of the Shuttle to minimize "up-front" costs led to greatly increased operating costs.[17] In order to avoid mortgaging future generations, any rescue system should be designed from the outset to minimize operational costs.

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[12] "Pad basing" as used here means having a launch vehicle stored on-site with a launch pad suitable for it available on demand. In practice, a vehicle would not be routinely sitting on a launch pad for long periods because the environment at existing launch sites is corrosive.

[13] "ACRC—CERV Phase A Studies, Book 1," NASA Johnson Space Center, JSC- 23265, Nov. 15, 1988, p. 4.18. See sec. 4.0 Reference Configuration Operations Studies/ 4.1 Emergency Timelines for Use of CERV.

[14] Ibid. sec. 5, General Operational Studies/ 5.3 CERV Daylight Landing Study.

[15] For initial work on this see, ibid. sec. 2.8, CERV Maintenance.

[16] Life-cycle costs include both the nonrecurring costs of development and procurement and the recurring costs of maintenance and operations.

OTHER RESCUE EXAMPLES

The need to provide means for rescuing crews working in isolated, hostile environments is not new. Other experiences with designing and using rescue capability might provide useful data for examining the risks and benefits of providing alternative crew rescue vehicles for the international Space Station.

- *U.S. Skylab:* During the Skylab space station missions, the United States maintained the ability to launch a rescue Apollo craft and outfitted it with a prepared "kit" kept in readiness at Kennedy Space Center. However, this rescue mission probably could not have been launched in less than 2 weeks under the best of circumstances. Also the Apollo vehicle that transported the crew to Skylab was kept attached to the space station during each mission, providing the crew with the means to reach Earth independent of ground launched systems.
- *U.S.S.R. Soyuz:* The Soviet Union keeps a Soyuz capsule attached to its space station *Mir* at all times when there is a crew on board. When a visiting crew reaches *Mir*, the older Soyuz, already at the space station, is used to return crew members to Earth. The Soviets have used their emergency return capability several times to return ailing crew.
- *Antarctic Research Stations:* Antarctic stations provide interesting analogues of the Space Station. Each research station typically maintains a backup station, kept physically separate from the main station. Usually, an old research building (some dating from the early 1950s) is kept supplied and operational in case of fire or other disaster that would cause the research crew to abandon the operational station. These older stations are physically separated to avoid the spread of fire and only maintained well enough to provide a backup capability. During the winter months, the stations are very isolated, but a few emergency rescue missions have been performed and supply drops are possible.[18] The various countries that maintain Antarctic research stations have also cooperated to rescue research parties in emergencies.

COOPERATION ISSUES RELATED TO STATION SUPPLY OR RESCUE

The United States has always maintained a vigorous program of international cooperation in space. As noted in an earlier OTA report:

> "U.S. cooperative space projects continue to serve important political goals of supporting global economic growth and open access to information, and increasing U.S. prestige by expanding the visibility of U.S. technological accomplishments."[19]

The Space Station is a major cooperative program in which the United States will provide the basic "core station," and Canada, ESA, and Japan will contribute sizable subsystems.[20]

Today, because other countries have developed their own indigenous launch capability, and because progress in space will continue to be expensive, cooperating on space transportation could be highly beneficial to the United States. For example, the United States could share responsibility for resupply of the international Space Station with its Space Station partners, and it could begin to share launch technology in a variety of areas where such sharing could be mutually beneficial.

ESA has proposed using the Ariane 4 and 5 launchers as alternative means for carrying cargo to the Space Station. The United States would gain additional assurance that critical cargo could reach the Space Station in the event the Shuttle or U.S. expendable launchers are for any reason unable to do so, which could save money and make the Space Station more effective. Europe would gain experience in automated docking systems and be able to use Ariane to make inkind contributions for Space Station operations, a much more attractive arrangement for European governments than one in which they contribute funding alone.

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[17] U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

[18] Delays of up to 2 weeks are not uncommon as a result of weather and equipment problems.

[19] U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities*, OTA-ISC-239 (Washington, DC: July 1985).

[20] Canada will contribute a servicing module and ESA and Japan will contribute pressurized laboratory modules.

In order for other countries to use their launch systems to supply the Space Station, or to dock with it, these countries will have to reach agreement with the United States on appropriate standards for packaging, docking, and safety. ESA and NASA have established a working committee to discuss these matters. If discussions prove successful, the experience of the committee could eventually be used as a basis for extending cooperative agreements to include cooperation on more sensitive aspects of space transportation.

In addition, Europe has proposed using the Hermes to carry crews to the Space Station and to service its Columbus module. Japan is also interested in using its H-II launcher for supplying the Space Station, and would eventually wish to employ its proposed spaceplane, HOPE, for the same purpose.

Cooperation could assist U.S. efforts in other ways. NASA estimates that developing a crew emergency return capability would cost between $1 billion and $2 billion, depending on its level of sophistication. NASA could potentially rely on space vehicles being developed by foreign partners for crew rescue. These include Hermes, HOPE, Saenger, or possibly Hotol (ch. 4). Several factors must be remembered, however. The Hermes crew would nominally be only three or four people, limiting its CERV capabilities in case the full Space Station contingent (8 crew) had to return.[21] Also, the scheduled date for permanently manning the Space Station is 1996 (although this date could slip). Hermes operational flights would start in 1999 or 2000 and its nominal orbit would be at 2 degrees inclination, far from the 28.5 degree Space Station orbit-making rescue more difficult and time consuming. The initial Japanese HOPE vehicle will not carry crew; a crew-carrying version may be developed early in the 21st century. A prototype Saenger could be finished by 2000 with an operational vehicle coming several years later. Hotol for most missions would be launched in an automated configuration and would not be ready until at least 2000. Use of an off-the-shelf Soviet spacecraft for rescue has been suggested as another international approach, although NASA has no plans to pursue this option.

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[21] Some have suggested that the United States could fund part of the European Hermes in order to speed up its development and to incorporate station rescue provisions in the design. This could cost the United States less than developing its own rescue vehicle.

Appendixes

Appendix A

Benefits and Drawbacks of Liquid Rocket Boosters for the Space Shuttle

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Potential Benefits

Safer Abort Modes

Figure A-1 and table A-1 give abort mode comparisons for different Shuttle/booster configurations. The Liquid Rocket Boosters (LRBs) allow a variety of safe abort modes, that is, several engines could fail on lift-off and still not cause a catastrophic mission failure.[1] A Solid Rocket Booster (SRB) or Advanced Solid Rocket Motor (ASRM) failure, however, is generally catastrophic because solids cannot be turned off after they are ignited. The LRB configuration consists of two boosters, each with four liquid-fueled engines. The ASRM and SRB configurations each consist of two solid booster rockets. All configurations rely on three Space Shuttle Main Engines (SSMEs) on the orbiter.

Long History, Potentially Greater Mission Reliability[2]

All major launch systems use liquid engines for part or all of the first stage; there is an extensive data base on their performance and use and fuel handling needs. LRBs can be test fired before launch. If the engine monitoring instruments indicate a problem, the engines can be shut down and the flight aborted on the pad. This is presently done with the SSMEs for a very short period before the solids are ignited.[3] Once a solid rocket is ignited it cannot be shut off—it burns through all of its fuel.[4]

The LRBs can also be tightly monitored during flight and can be shut down if a problem arises—perhaps before a catastrophic engine failure occurs. If the system were designed with sufficient margin, the thrust of the remaining engines could be increased to compensate for the shut-down engine, and the mission completed without requiring an abort mode.

Shutting down a liquid engine would present some problems of vehicle control in part because the control system would have to balance the thrust of a the remaining engines. Because the remaining engines can be throttled (unlike solids) it is possible to compensate for changed moments of force about the vehicle's center of gravity to reduce airframe stress and prevent cartwheeling. The failure of more than one engine would be even more difficult to compensate for. Control of these types of potential failures have not been thoroughly investigated.

Increased Lift Capability

The LRB performance improvement for the Shuttle could be an additional 20,000 pounds[5] to low-Earth orbit as shown in figures 3-7 and A-2.

Mission Profiles Can Be Changed Relatively Easily

As noted above, LRBs can be throttled while solid boosters cannot. Once a solid is poured to a predetermined configuration, its burn and hence thrust characteristics are set, fixing the direction and speed of the Shuttle on ascent. (Some flexibility is allowed by throttling the three SSMEs but this entails several potential problems and is avoided if possible.) These solid booster thrust characteristics sometimes change unpredictably when the solids age. In contrast, throttling LRBs within reasonable thrust ranges is relatively easy and can be used to compensate for different payloads, atmospheric conditions, desired trajectories or orbits, etc. This can lead to more ''efficient'' launches and perhaps slightly heavier payloads.

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[1] All of these assume that a single engine (or motor) failure does not affect the operation of any other engine (or motor). A catastrophic failure of one engine (or motor) could of course destroy the Shuttle (no abort mode).

[2] The reliability of liquid engines versus solid rockets is the subject of heated debate and increasing study. NASA is creating a database that covers every U.S. launch and full-scale engine test—over 1,300 liquid or solid propulsion events. It will include date, vehicle, engine type, top three anomalies (if there were problems) with corrective action taken, comments, documentation, and location of documentation. This database should be available soon. NASA intends to keep it updated with future launches and engine tests. Study of this database could help resolve some of the present uncertainty in liquid v. solids reliability statistics. (The Aerospace Corp. also has a significant database on engine successes and failures and the American Institute of Aeronautics and Astronautics has working groups analyzing these solids v. liquids reliability issues).

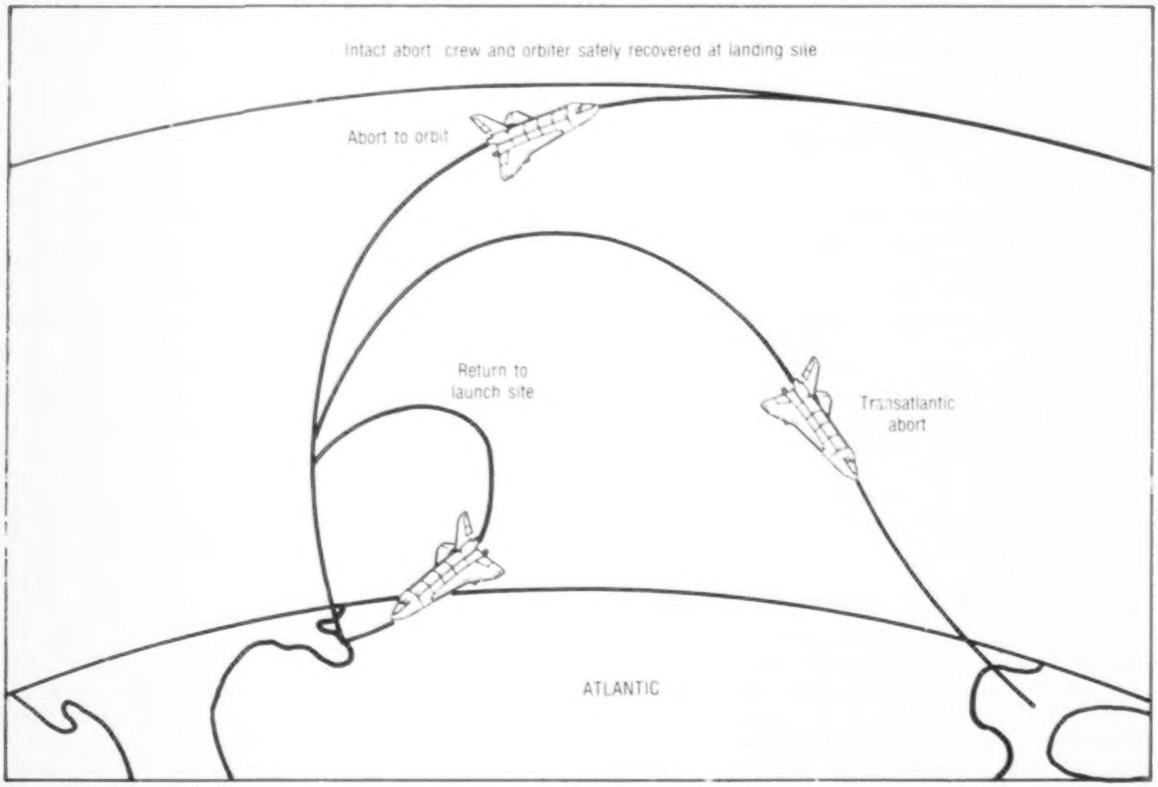
Some LRB proponents feel that arguing about solid versus liquid engine reliability is not germane; they believe that the probability of mission success, or the ability to abort a mission safely, are the critical points. They argue that even if a given LRB engine were slightly less reliable than a given solid rocket motor, because of the ability to shut down the liquid engine in flight, the mission reliability for the vehicle using LRBs would be higher than than for a vehicle using solid rocket motors.

[3] On one Shuttle mission, one of the three SSME's was shut down after the Shuttle was already well into its flight, and the mission was not affected. Shutting down an SSME takes about 30 seconds. The proposed LRBs are simpler engines and can be shut down essentially instantaneously (immediate fuel cutoff) thus making catastophic engine failure easier to avoid in case engine monitors detect an anomaly.

[4] In theory, if a solid is already ignited, one could provide a means to blow out the opposite end of the motor and ignite it also, yielding essentially zero thrust. However, the *other solid* (even if functioning properly) would also have to be ''shut-down'' in the same manner in order to prevent vehicle cartwheeling. With both solids essentially shut-down the Shuttle would have to be well into its trajectory to affect any reasonable abort. The jolts to the Shuttle system and connect points would also be severe and the Shuttle would probably break apart. Thus this is not a viable option.

[5] This performance increase, which is nearly double that planned for the ASRMs, would be possible in part because the LRBs would be longer and of greater diameter than the ASRMs. NASA held the diameter and length of the ASRM design to dimensions that would necessitate little or no alteration of the mobile launch platform. Because liquid engines would require fuel tanks that are larger than the ASRM dimensions to reach even 12,000 pounds additional thrust, NASA relaxed the geometrical constraints in the LRB design.

Figure A-1—Intact Abort Modes for Space Shuttle Missions


Intact abort: crew and orbiter safely recovered at landing site
Abort to orbit
Return to launch site
Transatlantic abort
ATLANTIC

A Shuttle orbiter is not expected to survive a ditching at sea, although the crew might escape and survive if controlled gliding flight is established before ditching.

SOURCE: General Dynamics.

Safer Shuttle Processing Flow

LRBs are fueled just before launch. SRMs, on the other hand, carry explosive fuel at all times and must be handled carefully. Safety considerations are a critical, and expensive, part of SRM use—from manufacture, to transport, to launch vehicle mating, to liftoff. At some points in the Shuttle processing flow, entire buildings must be evacuated while a handful of people cater to the solid rockets.[6] Liquid cryogenic fuels are well understood and have a good safety record.[7]

Lighter Structure Would Allow Horizontal Assembly

Empty LRB tanks are lighter than assembled solid rocket segments, which are stacked vertically. For example, the Soviet *Energia* heavy-lift launch vehicle is assembled horizontally and then raised to the vertical only shortly before launch. Horizontal assembly and transport is much easier than vertical processing.

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[6] Five or more days are lost during this procedure. Twenty to thirty people are idled.

[7] Hypergolics are dangerous and potentially detrimental to the environment, but these are not being proposed for LRBs. LRBs would use some form of liquid oxygen/liquid hydrogen fuels or perhaps liquid oxygen/hydrocarbon fuels. Hydrocarbons such as methane or kerosene are relatively benign environmentally.

[8] The heat of the exhaust of any of these rockets may produce small amounts of nitric and nitrous oxide from the nitrogen in the air, just as automotive and jet engines do.

LRBs Are More Environmentally Sound

The exhaust of an LRB fueled by liquid hydrogen would consist solely of steam. The exhaust of an LRB fueled by RP-1 (kerosene) or some other hydrocarbon would contain both steam and carbon dioxide, along with small amounts of other gases. In contrast, the exhaust of a typical solid-propellant rocket contains large amounts of hydrochloric acid.[8]

Synergisms With Other Programs

The proposed ALS launcher could use the same engines developed for the LRB, or vice-versa. The LRB, if developed, could be used as a stand-alone launch vehicle.

Potential Drawbacks

Technical Uncertainties

The engine technology is known but the engines do not yet exist. Other uncertainties exist as to whether LRBs should be pump-fed or pressure-fed,[9] what fuel combinations (LOX/LOH, LOX/HC)[10] to use and for which stages or even whether to look at different cycle concepts.[11] Earlier, NASA expressed a concern that the larger LRBs would place unacceptable loads on the Shuttle wings. Subsequent wind tunnel tests have shown that the wing loads are acceptable.

Long Development Times

NASA has estimated that if an LRB program started today, liquid boosters might not be available until at least 1997.[12] This long time period results from the stringent development and testing requirements inherent for a new engine, particularly one that must be "crew-rated." ASRMs themselves could not be on-line until 1994, and they represent less development risk than do the LRBs.

High Initial Cost

NASA estimates that LRBs would cost $3 billion. Pad modifications would cost about $0.5 billion. A new flight dynamics data base would also have to be generated. By comparison, the cost for the ASRMs is estimated at $1 billion DDT&E and $300 million for construction of facilities. At this point it is hard to know how accurate these estimates really are. Rocketdyne Corp. has suggested that it would be possible to build a much cheaper engine, based on its engine used on the Atlas II and Delta II expendable launchers.[13] If LRBs cost significantly more to develop than ASRMs, they could strain an already tight NASA budget.[14] However, developing LRBs in consort with ALS propulsion needs could actually be a cost-effective path and could help both the Shuttle and ALS programs.

Table A-1—Abort Mode Comparison of Shuttle/Booster Configurations

Engine failure[a]		Abort mode		
Booster +	SSME	SRB	ASRM	LRB
0	1	RTLS	RTLS	TAL
0	2	Split-S or ditch	Split-S or ditch	Loft-return
0	3	Split-S or ditch	Split-S or ditch	Loft-return
1	0	None	None	ATO
1	1	None	None	RTLS
1	2	None	None	Loft-return
1	3	None	None	Loft-return
2	0	None	None	TAL
2	1	None	None	RTLS
2	2	None	None	Loft-return
2	3	None	None	Loft-return

[a] Assumes engines fail at liftoff.

KEY: ASRM=advanced solid rocket motor; ATO=abort to orbit; LRB=liquid rocket booster; RTLS=Return to launch site; Split S=aircraft landing maneuver involving a reverse of direction and rapid loss of altitude; SRB=solid rocket booster; SSME=Space Shuttle main engine; TAL=transatlantic abort.

SOURCE: General Dynamics.

Unique Operational Requirements

The same pad could in theory accommodate both solids and liquids, but as a practical matter NASA would need to dedicate a unique pad to each during the transition from solids to liquids because fuel handling, launch tower needs, component logistics, etc. would differ from those on the current Shuttle system.[15] It may be too expensive to keep both forever just to increase resiliency—but this could be explored. For example, Pad B at KSC could

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[9] Pump-fed appears to have the advantage since, for one thing, pressure-fed would take 5 years longer to develop than pump-fed.

[10] Liquid Oxygen/Liquid Hydrogen or Liquid Oxygen/Hydrocarbon

[11] Such as the Pratt and Whitney split-expander cycle.

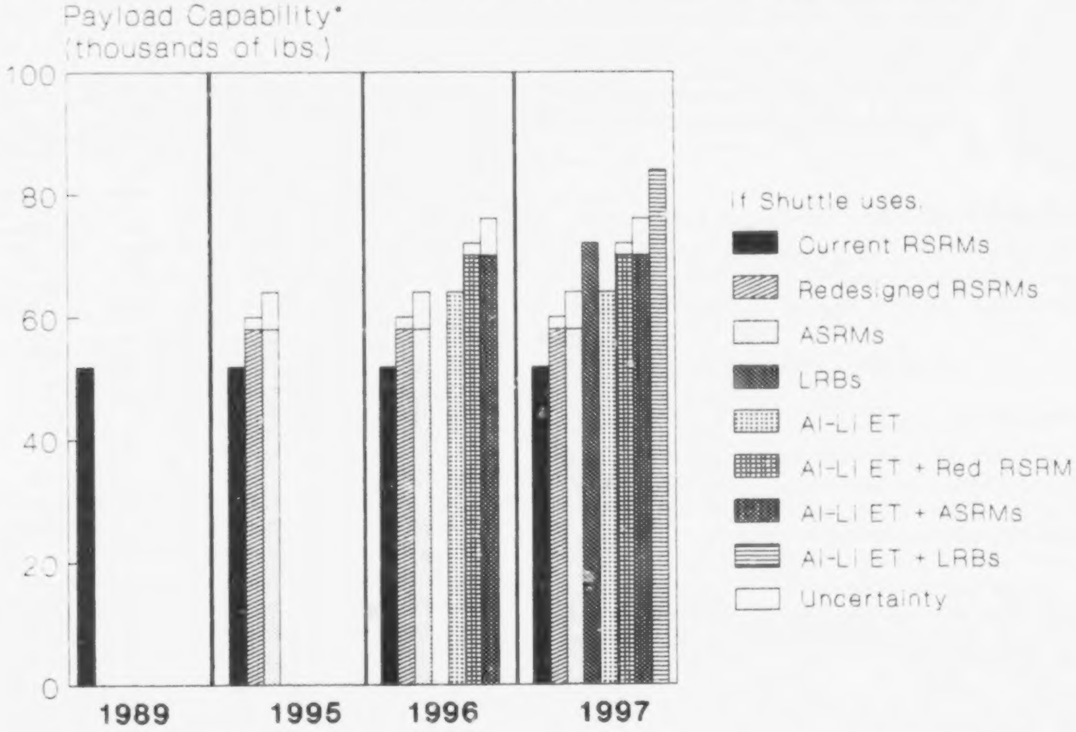
[12] If Phase B started in 1990 with several contractors competing, one winner could be chosen in 1991 for full-scale development. The LRBs would be ready for flight in 1997. However, in the Rocketdyne concept, the engines could be available earlier since much hardware already exists and is proven.

[13] Rocketdyne briefing to OTA, May 1989.

[14] This extra cost would seem small, however, if a solid rocket again destroyed a Shuttle. Loss of the *Challenger* cost the Nation between $7 billion and $13.5 billion, depending on how the accounting is done for the cost of failure. Yet, a new engine, like that needed for an LRB, would have its own significant risks of failure.

[15] Lockheed recently completed a study of operational changes which would be required at KSC in order to use LRB's on the Shuttle. "Liquid Rocket Booster Integration Study," Final Report, Vols. 1-5, Lockheed Space Operations Company report to NASA-KSC Advanced Projects and Technology Office, LSO-000-286-1410, NAS 10-11475, November 1988.

Figure A-2—Options for Increasing Shuttle Payload Capability v. Date of Availability



* To 110 n.mi. 28.5-degree orbit.

KEY: Al-Li ET = Aluminum-lithium external tank; ASRMs = Advanced Solid Rocket Motors; LRBs = Liquid Rocket Boosters; RSRM = Redesigned Solid Rocket Motor; RRSRMs = Redesigned RSRMs.

SOURCE: Office of Technology Assessment, 1989.

remain a solids facility while the presently unused Pad A could be converted to accommodate LRBs. One operational advantage is that processing in the vehicle assembly building (VAB) would be faster and less dangerous with liquid boosters.[16]

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[16] However, Shuttle turnaround time is constrained by orbiter processing, hence faster VAB processing does not necessarily mean faster STS turnaround times.

Appendix B

From Take-Off to Orbit—The X-30 Propulsion System[1]

For take-off, the X-30 will need an engine that can produce thrust from a standing-start. An example of such an engine is the *turbojet*. Air flowing into a turbojet is diffused and compressed before it is combined with fuel and ignited. The compressor is similar to a fan and is powered by a turbine driven by exhaust products. A limiting factor in the ability of turbojets to propel aircraft to high speeds is the ability of the turbine to withstand the high temperatures caused by combustion and compression processes. In practice, these problems prevent turbojets from propelling aircraft to speeds above approximately Mach 3. Even when aircraft speeds are supersonic, however, air speeds within the engine combustor remain subsonic as air is slowed during its passage through the turbomachinery.

An aircraft travelling faster than the speed of sound causes a shock wave as pressure builds up ahead of leading edges of the moving body. In effect, pressure disturbances that travel at the speed of sound build up faster than they can dissipate. In the *ramjet*, the compressor and turbine are eliminated, and instead, air entering the combustor is compressed by the compression wave ("ram action") generated by air entering a suitably shaped engine inlet. Ramjets thus require auxiliary propulsion to boost the velocity to a point where they can sustain combustion and generate thrust. In practice, supersonic speeds are usually necessary before ramjet propulsion becomes practical.

In order to facilitate mixing and burning of the fuel in the combustion chamber (combustor) of a ramjet, air is slowed to subsonic speeds by passage through a diffuser. The heating inside the engine that results from the transition to subsonic air speed and from fuel combustion places a practical limit to ramjet propulsion by hydrocarbon-based fuels, such as kerosene. Even with special materials and cooling to solve the material creep problem at high temperatures,[2] if the temperature rises too high the efficiency of the combustion process decreases because fuel is no longer burned completely.[3] For conventional ramjets this translates into upper limits on speeds of about Mach 5 to 6. However, the engine I_{sp} of ramjets falls off rapidly above about Mach 4 (figure 5-5).

For speeds up to approximately Mach 6 there are concepts for propulsion systems that combine turbo and ramjet operation. To propel vehicles faster than this with air-breathing engines requires a *scramjet* (supersonic combustion ramjet); an engine where compression, fuel mixing, and combustion all occur at supersonic speeds. This allows, in theory, an engine that could start to work at about Mach 5 and continue to produce positive thrust all the way to Mach 25. Hydrogen gas derived from liquid or slush hydrogen is planned as the fuel source for the scramjets. Its primary drawback to hydrogen is that its low mass density results in large containment structures.

There are several concepts for combining scramjets with lower-speed propulsion systems. However, as a result of several factors, the optimum engine design changes dramatically at the low- and high-speed extremes. A key challenge for X-30 designers is to maximize the performance of low- and high-speed propulsion cycles over their speed range. As the X-30 accelerates from takeoff to hypersonic speeds, designers plan to change the shape of engine air inlets by using variable panels and control internal engine geometry with movable structures. Still there are fundamental tradeoffs in design that are unavoidable.

Drag forces on an aircraft moving through the atmosphere increase as the square of the vehicle's airspeed and the power expended in overcoming drag increases as the cube of the airspeed. However, drag is also proportional to air density, which decreases with altitude. To minimize drag and aerodynamic heating, the X-30 will accelerate to high speed in the uppermost parts of the atmosphere where the air density is very low. However, generating thrust at near-orbital speeds requires an engine with large and efficient air intakes to capture enormous quantities of air—both because of the thin air at high altitudes and because air entering the engine is expelled after combustion at a relatively small increase in speed (although the mass flow is much higher at the higher speeds). In contrast, at low speeds, engines take in a relatively small amount of air and accelerate it (in the combustion process) to high speeds.

While a subsonic jet might have an inlet covering 15 percent of frontal area, to capture sufficient air at Mach 6 an inlet covering 70 percent of frontal area would be desirable. However, at orbital speeds (Mach 25) an inlet covering some 95 percent of frontal area would be needed.[4] The geometric cross section of the engine inlet is too small to achieve these figures. In practice, to capture the large amounts of air required for scramjets requires engine inlets where, in effect, the entire front of the aircraft functions as part of the engine inlet. This necessitates an integrated engine and airframe design.[5]

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[1] Some of the details of the NASP propulsion cycle are classified. However, the following discussion is illustrative of the propulsion concepts being explored by contractors working in the NASP program. A final engine design has not been chosen yet by the NASP Joint Program Office.

[2] Creep describes the deformation of a material thermally cycled at high temperatures.

[3] At high temperatures the products of combustion dissociate into molecular fragments. The dissociation process absorbs energy (most fragments fail to recombine in the nozzle) reducing the total kinetic energy of the fuel fragments, and thus lowering the thrust. See "The Pocket Ramjet Reader," Chemical Systems Division, United Technologies, Sunnyvale, CA, p.12.

[4] Engine inlet data from Dr. Robert Jones of NASA Langley.

On the other hand, a smaller engine inlet would be desirable to minimize drag for flight at low speeds and low altitudes. The size of the engine inlet is one design tradeoff. Another would arise if, as currently anticipated, auxiliary rocket-based power[6] were used to supplement the X-30's air-breathing propulsion system. Igniting rockets at relatively low hypersonic speeds might allow smaller scramjet engines and inlets but only at the penalty of decreased payload. Alternatively, if designers opt to keep payload constant the increased weight associated with rocket propulsion could be compensated by, for example, designing the X- 30 to have greater lift. Larger wings would provide more lift, but vehicle size, weight, and cost would increase too.

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[5] Pod mounted scramjet concepts were explored in the 1960s but researchers found that air inlets could not capture enough air and, in addition, there was excessive drag from support struts.

[6] The auxiliary propulsion system would use liquid oxygen carried on-board the X-30 to supply either the scramjet engines or a small, separate rocket. The term ''rocket-based power'' is used here to refer to either approach.

Appendix C

NASP Materials and the X-30 Materials Consortium

Materials Consortium

The five prime National Aerospace Plane (NASP) engine and airframe contractors have joined into a uniquely funded contract arrangement to demonstrate the production readiness of advanced materials critical to the success of the X-30. The Materials Consortium (officially designated as the NASP Materials and Structures Augmentation Program) places contractors, in competition for Phase III of the NASP program itself, in a cooperative arrangement. Each of the five contractors has lead responsibility for the development of one material type, including the fabrication processes to produce structures, but each also participates in the efforts of the others. All data developed by the contractors are shared equally on a nonproprietary basis, including industrial research and development (IRAD) that was completed or ongoing prior to the contract awards. In addition, a large portion of the funding is being transferred to subcontractors, universities, and research institutes directly supporting the prime contractors in advanced development work.

The Consortium members and their area of principal investigation are: General Dynamics—refractory composites (including carbon-carbon and ceramic matrix composites), Rockwell—titanium aluminide alloy development (Ti_3Al and TiAl) and scale-up effort, McDonnell Douglas—titanium metal matrix composites (including SiC fiber reinforced Ti_3Al), Rocketdyne—high conductivity materials (including copper matrix composites), and Pratt & Whitney—high creep strength materials (including monolithic and reinforced TiAl, using fibers composed of titanium diboride and alumina).

The consortium was funded in March 1988 at a budget of $150 million for a 30-month period. Recently, a subsystems consortium was formed to develop some 11 different systems including avionics and instrumentation, crew escape, slush hydrogen technology, and turbomachinery. As in the Materials Consortium, work in the subsystems consortium is being done on a nonproprietary basis. Both the NASP JPO and contractors appear highly satisfied with the consortium arrangement.

NASP Materials[1]

The X-30 airframe will utilize noninsulated, load-bearing hot structures without the thermal protection tiles of the shuttle. Where necessary, these hot structures will be cooled with hydrogen using several active cooling schemes. The projected structural designs for all areas of the vehicle call for high-stiffness, thin-gauge product forms that can be fabricated into efficient load-bearing components. These in turn require high strength, low density materials that can retain their properties up to temperatures beyond the capabilities of present day commercially available materials.

Current challenges center around scaling up laboratory production processes of advanced materials; developing fabrication and joining techniques to form lightweight sandwich and honeycomb structures; and forming materials and coatings that can withstand thermal cycling of the sort that would be seen in a flight vehicle. In addition, concerns about the possibilty of material fatigue must be resolved (see discussion of transient thermal fatigue in footnote 30).

The major classes of materials with promise for the X-30 are rapid solidification technology titanium aluminide alloys (RST Ti), metal matrix composites based on reinforced titanium aluminides (Ti-Aluminide MMC), high thermal conductivity materials, carbon-carbon (C-C) composites, and ceramic matrix composites.

Titanium-based materials are candidates for large portions of the X-30 external and internal structure. Currently available titanium alloys are lightweight and can withstand temperatures of 1,100 °F but in the X-30 even greater temperature tolerance is desirable to minimize active cooling requirements. Higher temperature, titanium-based materials are possible using recently developed rapid solidification technology. RST Ti-aluminide is produced when molten titanium and aluminum are dropped on a spinning disk that sprays small droplets of the material into a region of cold helium gas. The material cools at an extraordinary rate—up to one thousand degrees in one millisecond—and is transformed into a fine powder with unique properties. In particular, RST materials are not contaminated with oxygen and the sudden cooling produces a material without stratification or other nonuniformities.

At room temperature, RST aluminum displays similar strength to conventional aluminum. However, RST Ti-aluminides exhibit much higher strength and stiffness at high temperatures compared to conventional titanium alloys while having only one-half the weight of the material previously used at these temperatures. Alloy systems based on Ti_3Al can withstand about 1,500 °F and alloys based on TiAl can withstand about 1,800 °F. They are also lighter than the currently available high-temperature nickel alloys.

TiAl-based alloys are the most desired of the Ti-aluminides because of their combination of high-temperature tolerance, light weight, and greater resistance to hydrogen embrittlement. Their drawback has been that their brittleness makes it difficult to roll them into sheets, a necessary step to fashion sandwich panels. Some recent progress has been reported, but currently Ti_3Al-based alloys figure more prominently in near-term plans for the X-30 because of their greater ductility. Use of Ti_3Al-based alloys instead of TiAl would cause some increase in vehicle weight because their density is about 10 percent higher than TiAl. In addition, Ti_3Al is more susceptible to hydrogen embrittlement and would therefore require barrier coatings if actively cooled with hydrogen.

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[1] The material in this section draws extensively on Terence M. F. Ronald, "Materials Challenges For The National Aero-Space Plane," *Review of Progress in Quantitative Non-Destructive Evaluation* (New York, NY: Plenum Press, May 1989). See also: Ned Newman and Richard Pinckert, "Materials for NASP," *Aerospace America*, May 1989 pp. 24-26, 31; Alan S. Brown, "Taming Ceramic Fiber," *Aerospace America*, May 1989, pp. 14-22; and Jay G. Baetz, "Metal Matrix Composites: Their Time Has Come," *Aerospace America*, November 1988, pp. 14-16.

Metal matrix composites of titanium use embedded silicon carbide fiber to produce a material that is much stronger and stiffer than the unreinforced metal. Silicon carbide reinforced titanium can reportedly withstand temperatures of 1,500 °F and is a candidate material for thin panel structures that will form parts of the X-30's skin. There are several technology challenges associated with incorporation of the fibers into the matrix. Among them is the thermal expansion mismatch between fiber and matrix, leading to a propensity for cracks to appear in the low ductility matrix during formation of the composite or on thermal cycling.

One solution being pursued is the development of alternative reinforcing fibers that have a better thermal match, such as titanium diboride and titanium carbide. NASP is also setting up pilot plants to explore Ti-MMC composites formed with rapid solidification plasma deposition methods. Some success has been reported with Ti_3Al-matrix materials and work is underway to extend this to TiAl-based composites. A challenge for all Ti-MMC materials will be to develop methods for evaluating the presence of cracks in the fiber/matrix bond without compromising the integrity of the material. In addition, there is a concern with all fiber reinforced materials related to their reactivity at high temperatures with the host material.

Carbon-carbon composites (carbon fibers embedded in a carbon matrix) are candidate materials for heat shields and large portions of the X-30's skin. Carbon-carbon is one-third lighter than aluminum, retains its strength to very high temperatures, and has been used on the Space Shuttle leading edges and nose. On the Shuttle, carbon-carbon on the wing leading edge and the nose cap is exposed to temperatures as high as approximately 2,750 °F. Mission lifetimes of Shuttle C-C wing panels are currently 65 to 85 flights, but new sealant coatings are being introduced that will increase this figure to 100 flights. The challenge for NASP materials researchers is to create a material that is able to withstand repeated thermal cycling during the specified minimum of 150 X-30 flights.

At very high temperatures, untreated carbon-carbon would react with oxygen and form carbon dioxide. Researchers are testing a large number of protection schemes for carbon-carbon, including the application of special coatings that can form a barrier to oxygen, and the addition of oxidation inhibitors to the carbon matrix. The oxidation problem is exacerbated by the necessity on the X-30 to make carbon-carbon structures and oxidation coatings very thin to save weight. Although tests on samples of carbon-carbon materials during simulated NASP temperature-pressure cycles demonstrate increasing longevity, the durability of the composite is not yet equal to the materials used on the Shuttle.[2] The advanced carbon-carbon composites being developed for NASP are expected to provide greater strength than the C-C used on the Shuttle. With appropriate oxygen barrier coatings, temperature resistance to over 3,000 °F should be possible.[3]

Some parts of the X-30, such as leading edges and the nose cap, would exceed the temperature limits of carbon-carbon. In addition, these sections of the vehicle would be exposed to very high heat loads. Researchers are investigating the use of alternative composites that would be actively cooled as one solution to this problem. Ablative coatings of carbon-carbon are still another option; however, their use would increase maintenance and support costs.

On the Shuttle, carbon-carbon is placed on top of a metal load-bearing substructure. However, to save weight, carbon-carbon would be used at some locations in the X-30 as a load-bearing structure. Engineers have a particular concern with the use of C- C as a load-bearing structure because of the potential for cracks to form as a result of thermal cycling. Finding coating materials whose thermal expansion coefficient is close to that of the carbon-carbon substrate will be necessary to prevent cracks and subsequent oxidation of the substrate.

Joining of carbon-carbon is another area of concern. Close fitting of parts and control of surface finish is necessary because at hypersonic speeds small irregularities in surface smoothness, or gaps where materials are joined, could generate hot spots that would be sufficient to burn through surface materials. On the Shuttle, dimensional tolerances of carbon-carbon can be now be controlled to 0.010 inches.[4] Researchers expect similar performance will be available on the advanced carbon-carbon composites that would used on the X-30.

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[2] Recent tests with small samples of specially prepared carbon-carbon have withstood some 200 hours (roughly equivalent to 100 flights) of simulated NASP temperature and pressure flight profiles. However, researchers have not yet fabricated large structures with this material and there is some concern that the material will not retain its characteristics when fabricated in full-scale pieces. In addition, the material is relatively heavy because of its thick coating. Other types of carbon-carbon do not suffer from these problems, but they have not demonstrated as long a lifetime under simulated NASP flight profiles.

[3] Garland B. Whisenhunt, Director Carbon-Carbon Technology Applications, LTV Corp., briefing to OTA, May 30, 1989.

For operation above about 2,500 °F designers are also investigating the possibility of ceramic-matrix composites. These materials could form lightweight structures with better oxidation resistance than carbon-carbon. Historically, a problem with ceramic materials has been their brittleness and propensity to develop cracks. Researchers are attempting to find a reinforcement material for the ceramic matrix that will help alleviate this problem. Ceramic-composites are candidate materials for selected airframe applications, such as surfaces adjacent to the nose cap and leading edges of the X-30, and also for engine components and panels.

Two classes of ceramic-matrix materials are being studied. Glass-ceramic composites may be useful up to about 2,200 °F and can be fashioned into honeycomb-core panels and other complex shapes. They are a possible alternative to some titanium aluminides. Advanced ceramic-matrix composites, such as silicon carbide fiber inbedded in a silicon carbide matrix (SiC-SiC), are not as well developed as the glass-ceramics, but their resistance to hydrogen embrittlement makes them an attractive material for actively cooled hot structures. Again, the potential for cracking is a concern with all ceramic-matrix materials.

Graphite reinforced copper matrix composites are being studied for structures that will be actively cooled. This material is expected to be durable and it exhibits higher thermal conductivity (in the direction of the fiber), lower density, and higher strength than pure copper. NASP is exploring production methods for this material and is also investigating the possibility for creating other reinforced high thermal conductivity copper composites.

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[4] Ibid.

Appendix D

The Defense Science Board Report on NASP[1]

Among the most thorough outside technical reviews of the X-30 program to date is that of the Defense Science Board Task Force on NASP. The DSB task force, composed of eminent aerospace experts, was asked to evaluate the degree to which the technology base could support a decision for NASP to advance to Phase III—the design, fabrication, and flight test of a selected engine and airframe configuration.

Most of DSB's work was performed in the first half of 1987, although the study was not released publicly until October 1988. NASP officials believe some parts of the DSB study are now out of date and note that the DSB report occurred while airframe and engine configurations were still in a very preliminary design stage. In particular, vehicle designs being examined by the DSB closely resembled initial concepts that came from the Copper Canyon study of 1986. These concepts have been abandoned by NASP as overly demanding of near-term technology.

The DSB found that NASP was a vitally important national program and affirmed decisions to focus the program around the objective of achieving single-stage-to-orbit. However, the DSB also noted that, "early estimates of vehicle size, performance, cost, and schedule were extremely optimistic." The DSB concluded that NASP's Technology Maturation Program was inadequate to support NASP's schedule with an acceptable degree of risk.

In response to the DSB report and internal evaluations, NASP officials modified their schedule; focused their program on a small number of vehicle and engine options; established an elaborate risk-closure plan based on the achievement of a specific series of technical objectives or milestones; and combined the five major engine and airframe contractors in a novel Materials Consortium. NASP believes rapid progress has been made in the key enabling technologies of the X-30 since the DSB performed their study. A brief review of some of the DSB's conclusions and NASP's response is given below. Space allows only a cursory review of the many areas of technical concern.

In aerodynamics DSB found the greatest uncertainty in predicting the point at which air flowing smoothly over the vehicle (laminar flow) becomes turbulent. Lift decreases, drag increases, and heat transfer rates change when airflows become turbulent. Thus, predicting the location of this "boundary layer transition" has a profound effect on vehicle design. For example, the DSB noted that location of the transition point could affect the design vehicle take-off gross weight by a factor of two or more

As noted earlier, progress has been made in the ability of computational fluid dynamics to characterize the boundary layer transition since the DSB report. Furthermore, X-30 designers believe that a vehicle designed with "conservative" assumptions about the boundary transition—such as assuming laminar flow only between Mach 4 and Mach 15, and only over part of the forebody—would still allow a vehicle design that would meet the primary objective of single-stage-to-orbit. Nevertheless, until an X-30 undergoes flight testing there will be uncertainty regarding the adequacy of computational predictions.

In propulsion DSB expressed a large number of concerns including: the integration of a low-speed propulsion system with a ramjet/scramjet; the potential effect of combustion instabilities, transients, or even flameout during acceleration; engine performance at high Mach numbers; and the adequacy of knowledge of thermal loads (influenced by uncertainties in the boundary layer problem noted above). The DSB called for increased experimental verification to improve understanding of the complex NASP design. In particular, they suggested NASP consider performing fully integrated engine tests in a variable Mach wind tunnel.

To address these concerns, NASP officials plan to conduct over 20,000 hours of wind tunnel testing in Phase II of the program. These tests would include near full-scale wind tunnel tests at Mach 8. Additional Phase III engine qualification and certification tests are also being planned. Officials have rejected recommendations to improve hypersonic test facilities beyond what is already planned because of their cost (hundreds of millions of dollars) and long developmental lead times. Nevertheless, a recent National Research Council Air Force Studies Report considered the development of new hypersonic test facilities an urgent requirement.

NASP officials also believe that, based on their latest analysis and ground tests, the problem of large engine thrust changes or flameout (here collectively referred to as "unstarts") will not occur outside the range of Mach 2 to 8. To control engine unstarts within this region, NASP contractors are planning to implement engine designs that could survive the unstart condition, control the unstart, and be relit.[2] Safe mission aborts are also being designed. However, not all experts appear satisfied that the issue of combustion instabilities has been resolved.[3]

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[1] Report of the Defense Science Board Task Force on the National Aerospace Plane (NASP), (Washington DC: Office of the Under Secretary of Defense for Acquisition, September 1988).

Some of the details of the NASP propulsion system are classified, preventing a complete discussion here. NASP has reduced the number of potential engine types to two and will select one (along with one airframe) in late 1990. At least in principle, the problem of designing a propulsion system that can accelerate a candidate X-30 airframe from a standing start to Mach 25 has been solved. How well theoretical expectations match up to experimental performance would be demonstrated in a flight test program.

In addition to its concern with the pace of materials development, DSB was concerned with the lack of knowledge characterizing the behavior of potential materials when fashioned into aircraft structures—some of which would be subjected simultaneously to severe aerodynamic and aerothermal stresses. The large uncertainties in theoretical predictions, and the lack of an adequate experimental data base appeared especially worrisome given the design requirement to minimize structural weight. In fact, the DSB stated that the knowledge base at the time of their report was such that a decision to proceed to Phase III "is considered an unacceptable risk to program success and in fact could impose serious flight safety risks."

NASP officials have stated that if the technology is not sufficiently mature to support a decision to begin Phase III they will not do so, but will continue technology development until a positive decision can be made. Furthermore, there are contingency plans in most of the technical risk areas identified by JPO. For example, in the structures and materials program, a heavier material closer to availability may be substituted for a less mature material. The increased weight could be accommodated at a cost in payload; an increase in vehicle size, weight, and cost; or the substitute of rocket propulsion for scramjet propulsion (which in turn will lower payload or increase the vehicle's gross weight). The tradeoff process is an ongoing one. Since the time of the DSB report, several higher risk materials have been eliminated from consideration for use in the X-30 and the Phase III decision has been delayed 1 year to provide additional time to mature key technologies.

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[2] Between about Mach 1 and Mach 2 a shock wave must pass through the engine inlet without causing the engine to flameout. Changes in air flow patterns that cause a sudden loss of thrust must also be avoided. In addition, steady flow conditions must be maintained as engine operation is transformed from ramjet to scramjet mode. Unstarts can result in hazardous asymmetrical thrust conditions unless corrected quickly. They were a problem in early flights of the Air Force's high-altitude, Mach 3+, SR-71 "Blackbird" reconnaissance aircraft, but are now routinely controlled. In briefings and letters to OTA, Pratt & Whitney and Rocketdyne officials provided details of their methods to avoid and control thrust instabilities. Both contractors supported the NASP JPO contention that instabilities would not be a severe problem despite the reservations expressed in the DSB report, and more recently by the Air Force Studies Board Report.

[3] For example, see *Hypersonic Technology for Military Applications*. . ., op. cit, footnote 4

Appendix E

Recent Accomplishments of the NASP Program—An Abbreviated List Supplied By The NASP Interagency Office

The earlier discussion of NASP Technologies naturally focused on the technical challenges for the NASP program. This list, provided to OTA by NASP program officials, is provided to complement that discussion.

Detailed SSTO Vehicle designs from three aerospace companies:

- Polar orbit, fuel for powered landing with go-around.
- Design payload and 4X payload.
- Reusable air frame without refurbishment.
- Wind tunnel verification of subscale models to Mach 20.
- CFD verification of full scale design.

Detailed propulsion system designs from 2 engine companies:

- Mach 0-20 (airbreathing and rocket).
- Wind tunnel test of sub scale engines to Mach 7.
- Wind tunnel test of large combustor models to Mach 12.
- Mixing and over 95 percent combustion with wall injectors in 2-inch combustor.
- Wind tunnel tests of inlets to Mach 14 to 16.
- Demonstration of hydrogen film cooling for friction reduction and heat transfer reduction in combustor.

A completely new family of Full Navier-Stokes (FNS) and Parabolized Navier-Stokes (PNS) computer codes that caluclate air flow and reactions from nose to tail over complex geometries:

- Integrated into these analysis tools are: air reactions, combustion reactions, boundary layer characteristics, shock wave characteristics, flow interactions, and algorithms to expedite conversions of solutions.
- A fast solving PNS code that can calculate the flow characteristics from the nose, through the engine with combustion, and out the nozzle, including free-stream air interactions.

Greatly expanded hypersonic test capabilities:

- Low turbulence wind tunnels for prediction of boundary layer transition: Mach 6, Mach 20.
- GASL/NASA free piston expansion tube pilot operating with velocity to 25,000 feet per second.
- Rocketdyne large free piston shock tube (RHYFL) under construction for 1990 completion.
- Large engine test facilities (ETF) for test of large engine models have been constructed at Marquardt and Aerojet.

Active thermal control:

- Heat pipe cooling of nose and engine struts.
- Hydrogen cooling of inlet combustor and nozzle.

Structure:

- Integrated structure using fuel tank integrated with vehicle skin.
- Fuel storage and handling systems.
- Integrated thermal control systems.

Materials Development Consortium:

- Titanium-aluminide sheet fabrication and advanced carbon-carbon with new coating systems.
- Joints and fasteners of carbon-carbon and titanium-aluminide.

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